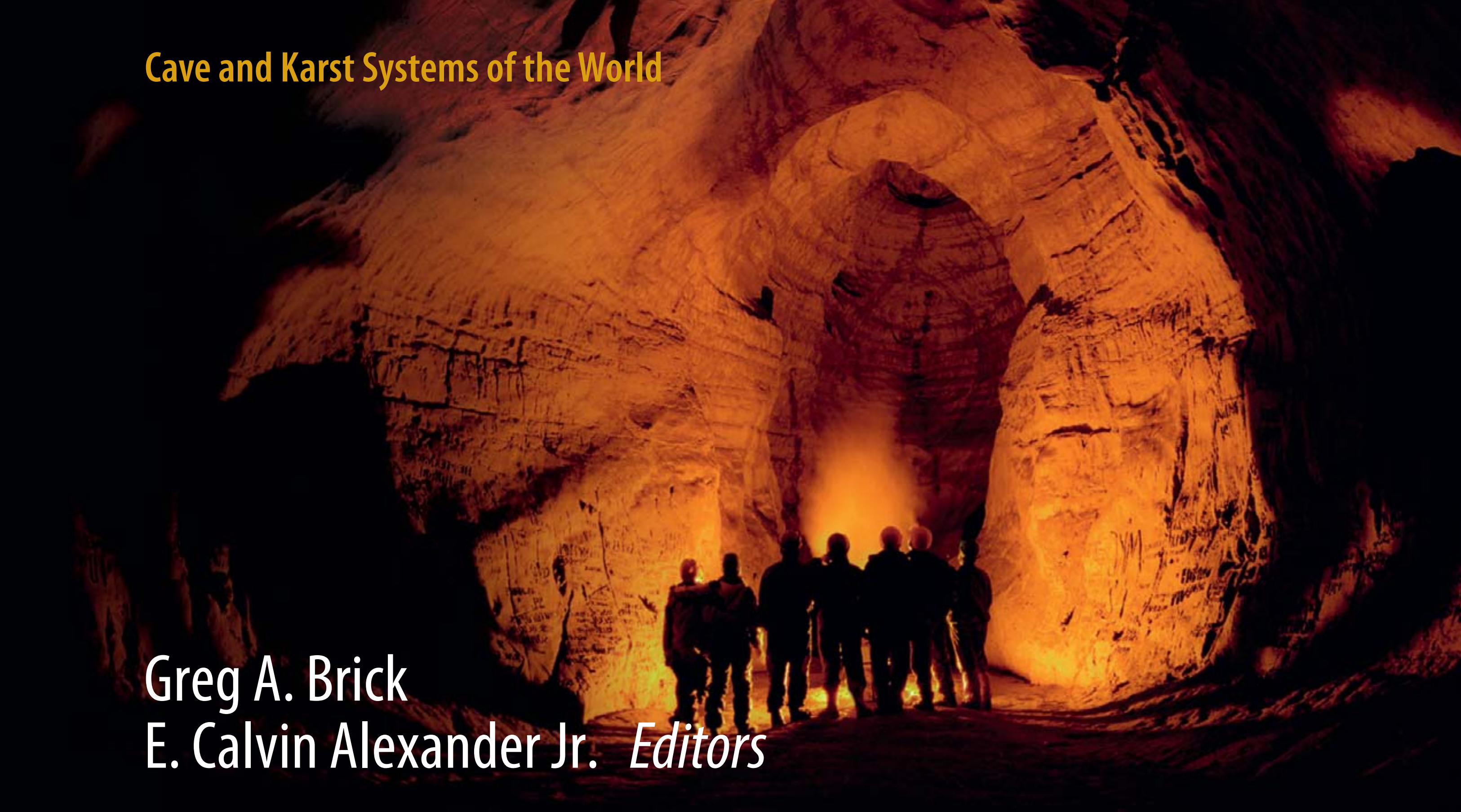

Cave and Karst Systems of the World

Greg A. Brick
E. Calvin Alexander Jr. *Editors*

Caves and Karst of the Upper Midwest, USA

Minnesota, Iowa, Illinois, Wisconsin

Springer

Cave and Karst Systems of the World

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The truth of nature lieth hid in certain deep mines and caves.—Democritus

Foreword

It was shrewd of the editors to ask me to write this Foreword, because I have little experience in their home territory and am presumably free of bias. But having spent much time elsewhere in caves and their surrounding landscapes, I can safely offer my congratulations on a job well done. The list of subjects covered by this book promises a level of discussion well beyond that of a simple tourist guide. It explains the basics of how water can pass underground through certain kinds of bedrock, dissolving channels that enlarge into caves, and how the overlying surface responds by developing depressions and sinking streams, to form what is known as a karst landscape. It goes much farther, investigating cave biology, history, archeology, and mining, as well as land management, the effect of past climates, and far more. The authors are among the most accomplished figures in American karst science. But except for them, few specialists in this field have more than a passing acquaintance with the Upper Midwest USA. That alone is justification for this book and its depth of coverage.

Many vacationers drive straight through this area on their way to higher ground, as though drawn by a magnet. In doing so, they are likely to miss the many curiosities that make this region special—small towns, isolated farmhouses, strange and specialized museums, amusing signs—all surrounded by gently rolling prairie and a feeling of peace. Most significantly, this quiet land is far more important to our economy and well-being than any number of majestic mountains. Preserving its fertility is a serious matter, and a significant part of that strategy is to understand the impact of karst. Land subsidence, soil degradation, flooding, and contamination can be major obstacles to productive land use. Proper land management is the only effective remedy, and this book provides the appropriate guidance. One of the most important goals of this book is to stress how to protect the soil and groundwater by adjustments in agricultural practices. The authors have gained much, or most, of their professional experience in the areas included in this book, and their insight extends far beyond its boundaries. Some are known worldwide for their skill at mapping caves and others for their insight into how to use cave deposits to interpret geologic history and ancient climates. The lead author of the section on cave biology began his cave studies in the heart of this region in the late 1950s and is still going strong.

In addition, several early specialists in the field, now long retired, spent large parts of their lives studying the caves and karst of this region. Of special note are the late J Harlen Bretz (no period after the "J"!), internationally famous for his early interpretations of cave origin and co-author of a book on Illinois Caves; James Hedges, prolific author and editor of descriptive cave literature; and David Morehouse, who, in a study of Iowa caves, was among the first to recognize the origin and enlargement of certain caves by sulfuric acid, a by-product of the reaction between oxygen-rich water and local iron-sulfide minerals.

Caves in the Upper Midwest USA have their own special character. Many of them have fissure-like outlines with long straight passage segments that intersect in a zig-zag pattern through the soluble rocks. Many others are truncated remnants of phreatic mazes high on ridge tops, making for mudbaths or painful crawling. Decorative "cave formations" (speleothems) are sparse but intriguing. The total mapped passage lengths of individual caves in this area range up to an impressive 17 miles, although the areas open to tours are limited to the most accessible and attractive sections. Some caves are quite challenging to explore, with deep shafts and cold lakes, but these obstacles are cleverly bypassed in caves open to tours. Minnesota has 490 known caves, two open to the public. Iowa contains 418, including at least five that are open to tours. Wisconsin has 367, one open to the public. Illinois contains 832 known caves, five or six open to tours. The karst areas of Illinois extend southward into younger rocks than those described elsewhere in this book, and they give a glimpse of the differences produced by variations in local geology.

Karst landscapes and caves are intriguing not only to scientists, but also to those who enjoy exploring and adventure. However, they pose a challenge. Without careful land management, there is a tendency for such areas to degrade rapidly by the subsidence and erosion of soil and the spread of contaminants. This is especially true during rainy periods. One of the most important goals of this book is to stress how to facilitate the protection of soil and groundwater by adjustments in agricultural practices.

My wife and I have only limited experience in the Upper Midwest USA. Still, our visits to this area have provided us with warm memories. A few decades ago we were engaged in fieldwork for the State of Minnesota at Mystery Cave, the well-known show cave. Determining how the structure of the limestone affected the origin and development of the cave was a satisfying experience. Twice we had a chance to lead visitors through it when there was a shortage of guides. Pointing out the attractions, we were glad to see how eager the groups were to understand the cave and to know where each passage led. Children were as interested as adults, and even more so where side-passages branched into darkness and we had a chance to turn on the lights and see for ourselves where they went. It helped that the two of us were as curious as the visitors.

One day, while we were mapping the cave's rock layers, we met a lone contractor who was busy with trail reconstruction. He had once worked at Disney World. "I wish I could spend a month working in here," he said—"I could make it look like a **real** cave!" We still laugh about that. Visitors find it an enchanting place, even though its walls are not pink and there are no fairies flapping overhead.

A couple of friends recently bought some property nearby that is surrounded by broad karst lowlands. Showing us around, the husband paused at a viewpoint overlooking the plain several dozen feet below. He quietly confided to us: "Looking out from here, your spirit just **soars**...."

We laughed quietly, but knew that he was right. With that kind of outlook, one can easily fall in love with our Upper Midwest karst!

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Preface

The Upper Mississippi Valley was recognized as one of the "important karst regions of the Northern Hemisphere" by Herak and Stringfield (1972, p. 470–471). Yet it's been 40 years since the publication of the 1980 NSS Guidebook on the caves of Minnesota, Wisconsin, and Iowa, edited by Alexander (1980), which over time became the most heavily cited speleological work on the part of the United States covered in the present volume. To this roster we now add a fourth state, Illinois, the states arrayed symmetrically around the Upper Mississippi River. While the editors realize there are many differing opinions as to what states constitute the Midwest, let alone the Upper Midwest, these contiguous states will be referred to as the Upper Midwest, or the Upper Mississippi Valley (UMV) region, in this book.

During those 40 years our understanding and stewardship of caves and karst has advanced significantly. There has been the widespread recognition of hypogene processes, the refinement of AMS radiocarbon dating, dye tracing to define springsheds, the use of LiDAR, and the establishment of the Minnesota Cave Preserve and other karst conservancies. With the discovery of many more caves in the interim, the time is ripe for a new overview of the region. In doing so, and in keeping with modern conservation practice, the exact locations of ungated wild caves are not disclosed.

While each state is described in a separate chapter, the introduction gives a seamless overview of the entire region, correlating the separate stratigraphic nomenclatures of the four states. The geologic names provided within Chap. 1 have been reviewed for conformance with the usage of the U.S. Geological Survey and the standards of the North American Stratigraphic Code. Geologic names provided in all other chapters have not been rigorously reviewed and thus are the sole responsibility of the respective authors. (When in doubt about the use of a particular stratigraphic name, we suggest consulting the generalized correlation charts in Figs. 1.6 and 1.9 in Chap. 1.) Special attention is then given to the lead-zinc mining region, biology, agriculture and karst, paleoclimate research, in separate chapters. A significant array of advances in karst science originated largely in the Upper Midwest, and these are described in the context of the various fields concerned, in a separate chapter.

Active caving groups in all four states have found, explored, and mapped new caves. Countless anonymous "sherpas" have contributed to the karst science efforts. Critical masses of research scientists at the State Universities and staff at the State Geological Surveys, Regulatory Agencies, and Soil and Water Conservation Districts in each of the four states recognized the significance of karst phenomena—as did the USGS, USDA, and USEPA. These groups, in a very synergistic and cooperative way, have researched, mapped, monitored, and informed the areas' residents about the impact and limitations imposed by karst phenomena on human activities and vice versa. "Karst" has progressed from an unknown, esoteric geographic term to an important consideration in the everyday lives of people in the area. For example, it is no longer socially acceptable to use sinkholes as convenient garbage and waste disposal sites.

The advances in karst hydrogeologic sciences have been funded by federal, state, local, and private grants to a wide range of individual researchers, organizations, and agencies. That funding has been matched by years of volunteer time and effort by innumerable people. The paleoclimate research has been funded primarily by federal research grants to the research

universities. The many individuals and organizations who have supported the karst science advancement are gratefully acknowledged.

St. Paul, MN, USA Greg A. Brick
Minneapolis, MN, USA E. Calvin Alexander Jr.

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Karst Geology of the Upper Midwest, USA

1

Daniel H. Doctor and E. Calvin Alexander Jr.

Abstract

Karst in the Upper Midwest occurs within a thick sequence of mixed carbonate and siliciclastic Cambrian through Pennsylvanian sedimentary rocks, with a minor occurrence of karst in Proterozoic sandstone. Deposition of the sediments occurred on a marine epeiric ramp that spanned much of the North American continent through most of the Paleozoic. The Upper Midwest region experienced dramatic changes in sea level over geologic time, resulting in the observed sequence of interbedded carbonate and clastic rocks. The greatest degree of karst development occurs within (1) the Lower Ordovician Prairie du Chien Group below the Sauk-Tippecanoe (Knox) unconformity, (2) the Upper Ordovician Galena Group, (3) the Middle and Upper Devonian Wapsipinicon and Cedar Valley Groups, and (4) the Middle Mississippian Mammoth Cave Group and correlative formations. Uplift and exposure of the rocks likely occurred in the Permian, with some later deposition of Cretaceous terrestrial sediments atop the marine strata. Nearly all the Cenozoic sedimentary units were removed by ice sheets during the Pleistocene; however, pockets of Cretaceous sediments persist on the margins of the Driftless Area, a region of the Upper Mississippi River Valley that remained largely free of ice during the last ice age.

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1.1 Introduction

Travel due east on US Interstate 90 from Austin, Minnesota, toward the Mississippi River, and you traverse one of the great karst regions of central North America. Moving across the great flat plains of the upland plateau one sees wide expanses of fields planted in corn, soybeans, and alfalfa that mark a seemingly never-ending horizon. Continue east on Minnesota Highway 16 after passing through the village of Spring Valley, and with a sideways glance out the window you might catch sight of the crown of a tree that stands alone in a field, its trunk hidden from view as if pulled vertically down into the Earth. One, two, three more sunken trees appear like as many gophers peering out of their burrows. The trees are sunken reminders of a once wooded plain, now entirely reclaimed for agriculture, except for the natural closed depressions that enclose isolated arbors. Cross the sinkhole plain along a spur of the plateau that is dissected by headwater stream valleys on either side, and you enter the town of Preston and descend off the plateau down into the valley of the Root River, a spring-fed designated trout stream. Bluffs of stratified pale yellow and gray rock peek through the winding, tree-lined river valley. Aided by the cool waters of springs emanating from vertical fissures and bedding plane partings in the bluffs, the Root River has incised its way through layer upon layer of limestone and dolostone, cutting a path to join the Mississippi River just south of La Crosse, Wisconsin. Some of the voids in the bedrock are wide enough that they beckon to be explored, holding the promise of passage into a hidden underground maze.

This is the karst of the Upper Mississippi Valley (UMV), formed across a time span of more than half a billion years by geologic processes that first built up then sculpted down the landscape to its present appearance. The geologic history of the region is tied to the constructive and erosive power of water: water of seas from hundreds of millions of years ago, water of ice from hundreds of thousands of years ago, and

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water of the present day that continues to shape the landscape. Water is not only the key to the geologic past, it is also the key to the more recent human history of the UMV region. The present human interaction with the landscape depends on its water resources, and those water resources are the key factor that will determine the future of the region. As in most karst regions, humans were drawn to settle in the UMV because of the abundant and readily available water resources provided by the karst aquifers. Continued economic growth and prosperity of the region rely on sustainable use and management of those aquifers. How might the water resources of the region be impacted by human land use, and how does the geologic history of the region help us to better understand those impacts? To begin to answer those questions, we need to look at what lies beneath the surface.

Figure 1.1 is an artist's rendering of what a block of earth cut out from southeastern Minnesota might look like if lifted out of the ground. At the surface, rolling hills covered in lush vegetation and crops sustain farming communities. The vegetation is rooted in a mantle of soil and sediment that blankets stratified layers of sedimentary rocks, mostly carbonates intercalated with shales, siltstones, and sandstones. The history of the deposition of these layers of sedimentary rock is where we begin to take a step back in time.

1.2 Paleozoic Geology and Paleogeography

Karst in the upper midwestern states of Minnesota, Wisconsin, Iowa, and Illinois is formed within a stratigraphic sequence of carbonate rocks (limestone and dolostone) that are interbedded with siliciclastic deposits of sandstone, siltstone, and shale. The geologic history of these sedimentary rocks began in the early Paleozoic Era, approximately the last 500 million years of Earth history. The oldest rocks that are currently exposed at the surface in the region were deposited as nearshore and shallow marine sediments that accumulated onto a stable foundation of crystalline igneous and metamorphic basement rocks of the North American craton. The marine sediments blanketed the basement rocks and subsequently were buried, compressed, and solidified through the process of diagenesis whereby loose grains of sediment were cemented and transformed into sedimentary rock. These sedimentary rocks were uplifted in the late Paleozoic, and some layers of overlying rock were eroded to reveal those exposed at present.

A simplified geologic map of the region is shown in Fig. 1.2 with the geologic units displayed according to the time at which the predominantly carbonate rocks were deposited. This figure illustrates where shallow, nearshore

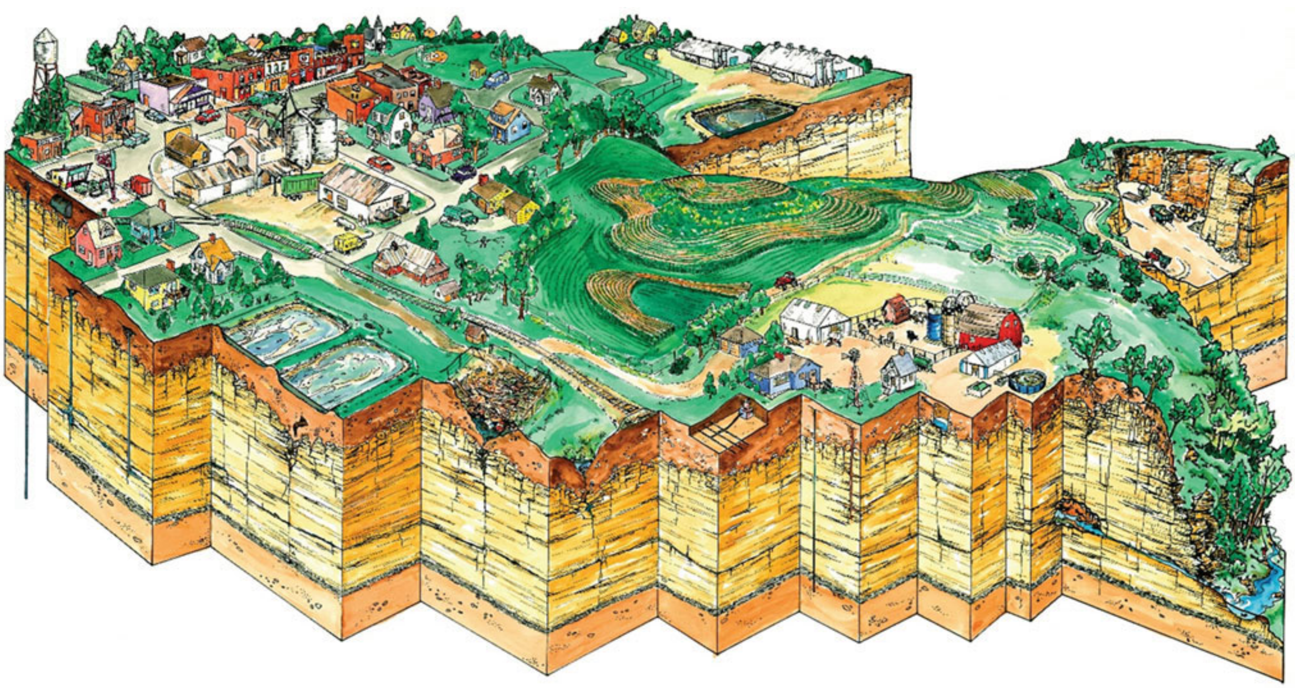

Fig. 1.1 Block diagram of southeastern Minnesota karst surface and subsurface (image used with permission of the Southeast Minnesota Water Resources Board)

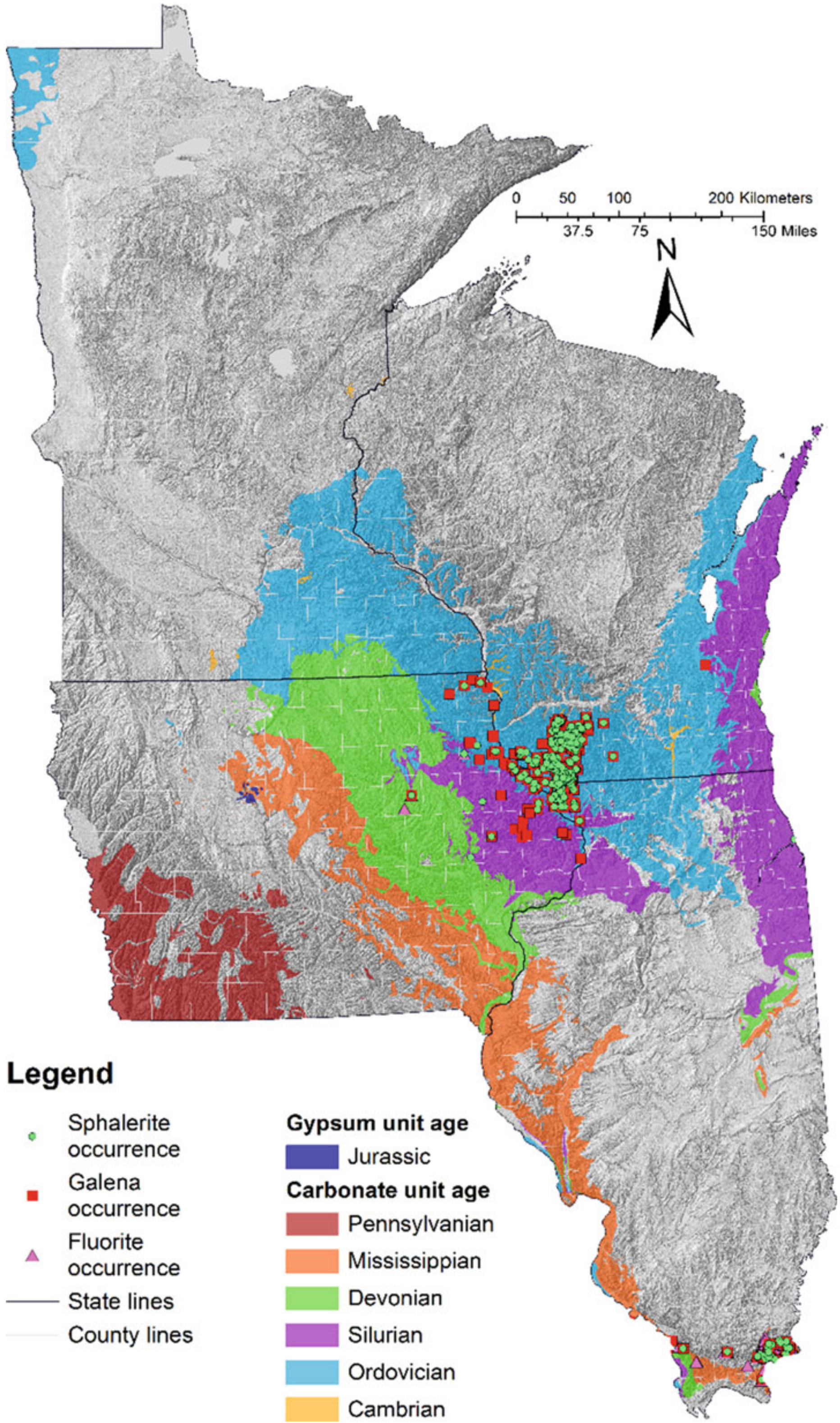

Fig. 1.2 Soluble bedrock geologic map of Iowa, Minnesota, Wisconsin and Illinois showing mineral occurrences. The carbonate rocks range from the Cambrian to the Pennsylvanian. The youngest Paleozoic carbonate strata are exposed only in southwestern Iowa, where karst development is not well expressed at the surface as result of overlying glacial deposits. Much younger Jurassic evaporite deposits occur near Fort Dodge in central Iowa and host gypsum karst

marine to deeper carbonate ramp environments were located at different periods of geologic time. Changes in sea level during sediment deposition and tectonic warping of the initially near-horizontal layering account for the map pattern. Also shown in Fig. 1.2 are the locations of mineralization in the rocks caused by the migration of metal-bearing brines that deposited zinc and lead sulfide minerals and associated fluorite. These ores are called Mississippi Valley Type (MVT) deposits due to their localization in this region and further to the south. See Dockal (2020), Chap. 7, this volume.

During the Middle and Late Cambrian (ca. 513 to 488 Ma) and through the Ordovician (ca. 488 to 444 Ma), the area of the North American continent that was exposed as land above the world ocean was much smaller, roughly half the size of the present-day continent (Fig. 1.3). This paleo- continental land mass is known as Laurentia, the center of which would have been located just south of the equator (Runkel et al. 2012). Laurentia was in a tropical to sub-tropical climatic zone across much of its extent; however, at that time in Earth history vascular land plants had not yet evolved and the land surface would likely have been a sparsely vegetated, barren, desert-like environment of rock, sand, and finer sediments. As a result, much siliciclastic sediment eroded off this landmass and was deposited in the adjacent shallow marine environments (Runkel et al. 2007). Fringing this landmass on its paleo-western side was the Iapetus Ocean, within which an enormous shallow bank of siliciclastic and carbonate sediment built up and covered the crystalline basement rocks of the Proterozoic craton (Fig. 1.3).

Although the North American continent shifted position over millions of years, the basement topographic features of the Transcontinental Arch, Wisconsin Dome, Forest City Basin, Illinois Basin, and Michigan Basin persisted. The processes responsible for the formation of the large regional basins in the surface of the crystalline craton have been attributed to fault-controlled mechanical subsidence and thermal subsidence under tensional stress during rifting, and flexural foreland subsidence resulting from orogenic episodes (Klein and Hsui 1987; Armitage and Allen 2010). The distribution and thickness of sedimentary cover that filled the basins evolved in response to sea level changes, sediment supply from adjacent emergent highlands, and broad tectonic warping of the interior craton. Sediments that filled the basins during submergent episodes record a history of approximately 175 million years, from the Late Cambrian to the Pennsylvanian.

1.2.1 Paleozoic Depositional Environments

In southeastern Minnesota, northern Iowa, northern Illinois, and southwestern Wisconsin, the Paleozoic sediments were deposited during multiple cycles of transgression (sea level rise) and regression (sea level fall) within a shallow marine ramp called the Hollandale Embayment. The embayment was a depression between regional basement highs of the Transcontinental Arch to the west, and the Wisconsin Dome to the east (Fig. 1.3). As a result, a single snapshot in geologic time would capture a position of the marine margin that would likely differ from earlier or later times. Due to the constantly shifting position of the paleoshoreline, a timeline passing through the rock strata of the basin would cross changes in lithologies related to the depositional environment or facies. Such changes in facies during the Late Cambrian are shown schematically in Fig. 1.4 (Runkel et al. 2007).

The Hollandale Embayment was a marine ramp that sloped to the south into the Forest City Basin that underlies most of Iowa. At present, the Paleozoic strata dip in general to the southwest at 1.9–2.9 m per km (Alexander 1980).

Most of the carbonate rocks in the region are a mixture of calcium-carbonate-dominated limestones and magnesium-carbonate-dominated dolostones. Fine siliciclastic sediment is abundant throughout the section, but siliciclastic input varied greatly as the sediments were deposited. The large supply of fine siliciclastic sediment onto the carbonate bank resulted in numerous layers of sand, silt, and clay that interrupted carbonate deposition. As will be discussed later, some of these siliciclastic layers have had an impact on later diagenesis and solutional development within predominantly carbonate rocks.

Deposition resulted in a large buildup of sedimentary rocks that were uplifted and exposed, and that host the karst features of the greater UMV region. The thickness of the carbonate-dominated sequence varies greatly according to the depositional environment and its relation to regional structures (e.g., Kolata 2005), but the stratigraphic section generally thickens toward the south and east from southeastern Minnesota into the interiors of the Forest City Basin and the Illinois Basin. In the Twin Cities of Minnesota, the thickness of the Paleozoic section is approximately 610 m (2,001 ft), while in central Illinois the thickness is more than 4 km (13,123 ft). This increase in sediment thickness is the result of a progressive deepening of the marine environment moving offshore along an epeiric ramp (Fig. 1.5).

Fig. 1.3 Laurentia in Late Cambrian time (©2013 Colorado Plateau Geosystems Inc.). The land area of the Upper Midwest was covered by a shallow sea that resulted in the thick accumulation of carbonate rocks that host karst features today. The Forest City Basin, Michigan Basin, and Illinois Basin are depressions in the basement rocks of the North American craton where thicker amounts of sedimentary rocks accumulated, yielding economic hydrocarbon and mineral deposits in many areas

Rocks that were once deeply buried have become exposed at the surface today as result of tectonic uplift and prolonged erosion. The rocks are thought to have been buried beneath approximately 600–800 m (1,970–2,620 ft) at the time of MVT ore deposition based on temperature reconstructed from mineral fluid inclusions (Bailey and Cameron 1951). The major tectonic episodes of mountain-building, or orogenies, that affected the rocks of the region occurred along the margins of the North American continent but transferred stresses into the continental interior that warped and deformed the existing sediments. The last major orogeny to impact the eastern and south-central portion of

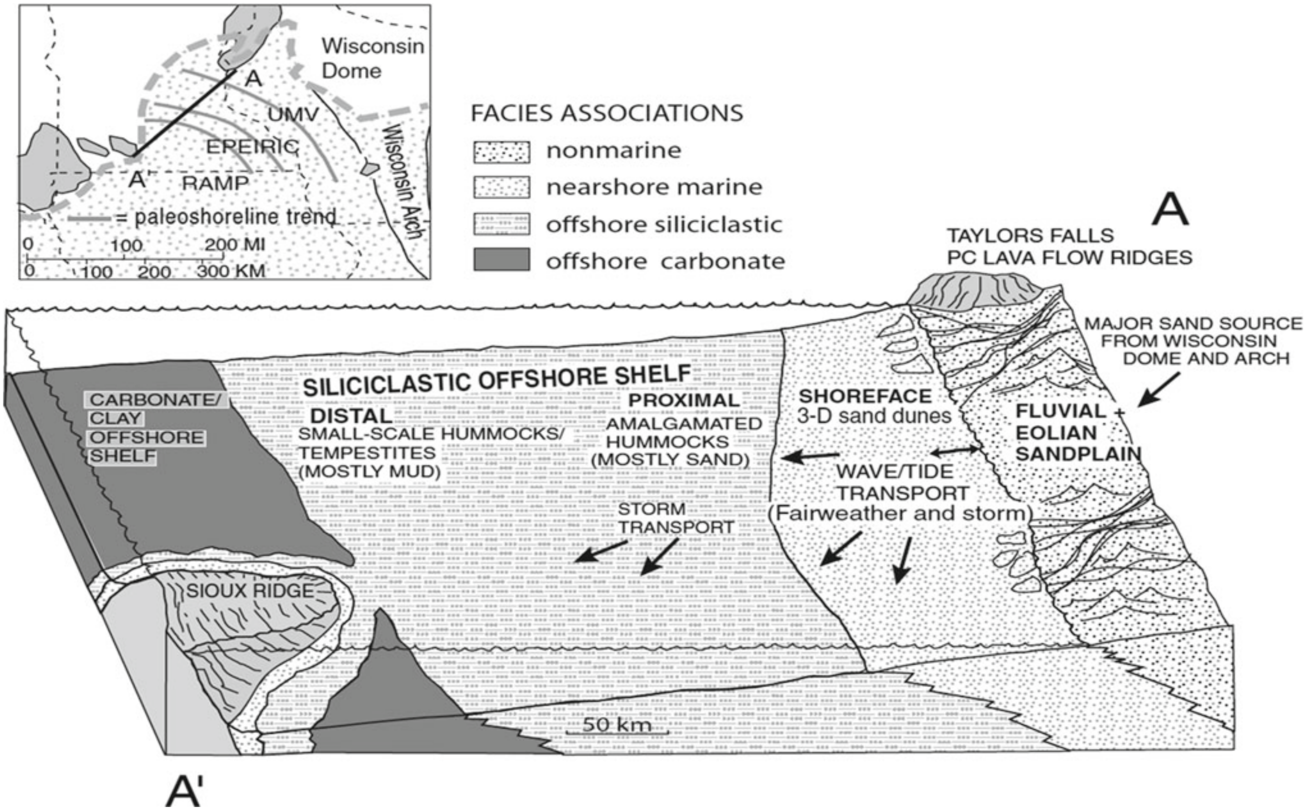

Fig. 1.4 Schematic block diagram illustrating the different depositional environments represented within a snapshot of time in the Late Cambrian (from Runkel et al. 2007)

USA was the Alleghanian orogeny that occurred between approximately 320 to 260 million years ago, during which the Appalachian and Ouachita Mountains were uplifted.

1.3 Stratigraphy of Karst-Bearing Units

Nearly all karst development occurs in carbonate rocks; exceptions include cave development in Proterozoic sandstones in Pine County, Minnesota (Shade 2002; Shade et al. 2015), and caves in other sandstones such as the Ordovician St. Peter Sandstone (see Alexander and Brick 2020, this volume). Although detailed stratigraphic correlations are beyond the scope of this chapter, generalized stratigraphic correlation charts are shown in Fig. 1.6 for the Cambrian through Silurian, and later in Fig. 1.9 for the Devonian through Jurassic to facilitate the comparison of stratigraphic formation names between States and in the subsequent chapters of this volume. The names presented herein conform with formal usage currently accepted by the US Geological Survey but may differ from earlier usage or informal names used in various states.

1.3.1 Cambrian System

The earliest Cambrian sediments covered an interval of Proterozoic clastic sediments derived from the erosion of the underlying crystalline and metamorphic basement rocks. Overlying the Proterozoic clastic rock is the Mount Simon Sandstone, found throughout the region. The Mount Simon serves as a regional aquifer, providing water generally of good quality for domestic use. Above the Mount Simon are a series of sandstones and finer grained siliciclastic units that extend throughout southeastern Minnesota, northern Iowa, and southwestern Wisconsin. These are represented by the Eau Claire, Bonnterre, and Wonewoc Formations, and the Tunnel City Group. Cambrian sandstones in Wisconsin are valuable resources of frac sand, as windblown sands on the shorelines of the Paleozoic seas caused rounding and sorting of sand grains in the deposits, making them ideal for use as fracking proppant.

A prolonged period of carbonate deposition occurred throughout the continent of North America resulting in a thick sequence of Upper Cambrian through Upper Ordovician rocks. The resulting stratigraphic succession is referred

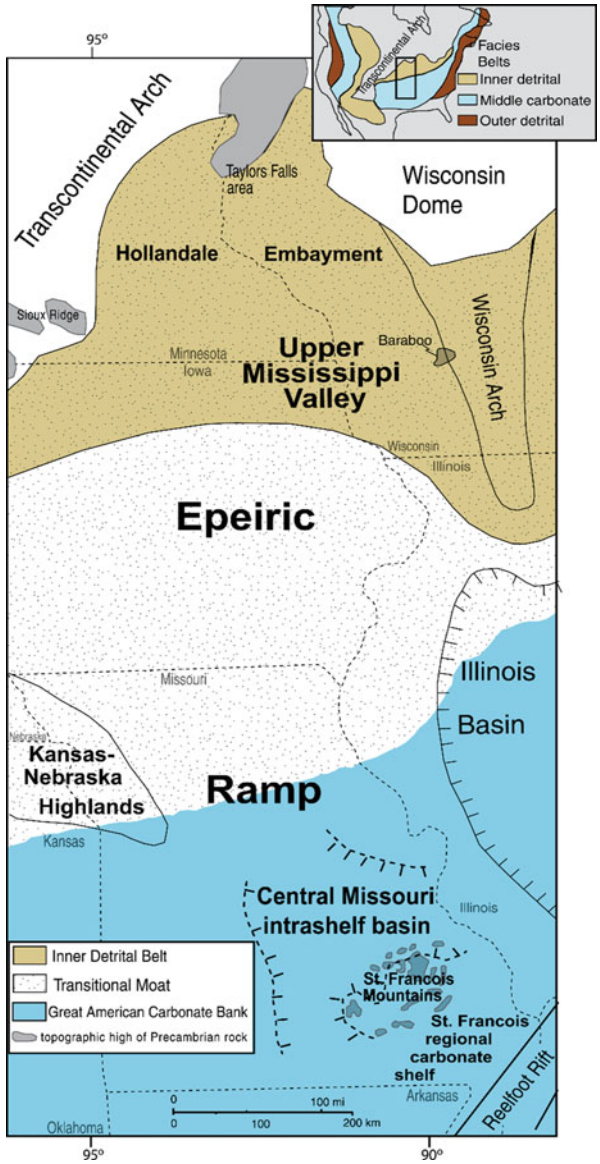

Fig. 1.5 Schematic map illustrating the change in depositional environment across the upper Mississippi valley during the Late Cambrian (from Runkel et al. 2012)

to as the "great American carbonate bank" (Fritz et al. 2012). In the UMV region, the sedimentation of this interval can be divided into two packages: a lower primarily siliciclastic sediment package and a successive package of primarily carbonate sediment (Runkel et al. 2012). The deposition of primarily carbonate sediments began near the Cambrian-Ordovician boundary following the deposition of primarily sandstones and other siliciclastic rocks mixed with some carbonates in the Upper Cambrian.

The area of the Hollandale Embayment was especially shallow in Late Cambrian time, resulting in deposition of mostly sand, silt, and clay mixed with some carbonate, and represented by the upper part of the Tunnel City Group (Franconia Formation), the St. Lawrence Formation, and the Jordan Sandstone (Runkel et al. 2007). While predominantly siliciclastic deposition occurred in the northern part of the UMV in Late Cambrian time, carbonate deposition of the Potosi Dolomite and Eminence Dolomite was occurring further south in Illinois and extending into Missouri. An interval of mixed carbonate and siliciclastic sediments in the Upper Cambrian strata of the northern portion of the UMV region is represented by the St. Lawrence Formation. As a result of the mixture of these sediment types, the St. Lawrence has been described as an "aquitardifer" due to its low vertical transmissivity but high horizontal solutional transmissivity developed at the stratigraphic boundaries between the intercalated siltstone and carbonate layers (Anderson et al. 2011; Runkel et al. 2018). Overlying the St. Lawrence Formation is the Jordan Sandstone, another regionally important sandstone aquifer.

1.3.2 Ordovician System

Above the Cambrian-Ordovician boundary, a relatively brief depositional hiatus occurred (Mossler 2008). The erosional surface was covered by carbonate rocks of the Prairie du Chien Group (Fig. 1.7). The lowest of three main karst systems within the Paleozoic stratigraphy is formed within this stratigraphic interval as illustrated in Fig. 1.8 (Runkel et al. 2014). In Minnesota, Wisconsin, and Iowa, the Prairie du Chien Group is composed of the Oneota Dolomite and the overlying Shakopee Formation. The boundary between the Oneota and the Shakopee is marked by a significant depositional hiatus and is a paleokarst horizon in southeastern Minnesota, with paleokarst features prominent in quarry exposures (Alexander and Wheeler 2015). Crystal Cave, the largest commercial cave in Wisconsin, is hosted within the Prairie du Chien; the upper levels are in the Shakopee Formation, and the lower levels extend into the Oneota Dolomite where spongework passages occur (Day 2009). In northern Illinois and parts of southeastern Wisconsin, the depositional hiatus between the Oneota and Shakopee may be absent, and further to the south and east these units are separated by the New Richmond Sandstone or Roubidoux Formation.

Following deposition of the Prairie du Chien Group, one of several major continental-scale periods of erosion, or depositional unconformities, occurred. This period of erosion divides the Sauk and Tippecanoe major depositional episodes on the interior of North America (Sloss 1963) and may have lasted over 10 million years, from the Early to Middle Ordovician. Evidence is found throughout the continent for paleokarst development in carbonate deposits exposed during this time interval. In the southeastern United States, the carbonate rocks that were deposited prior to being

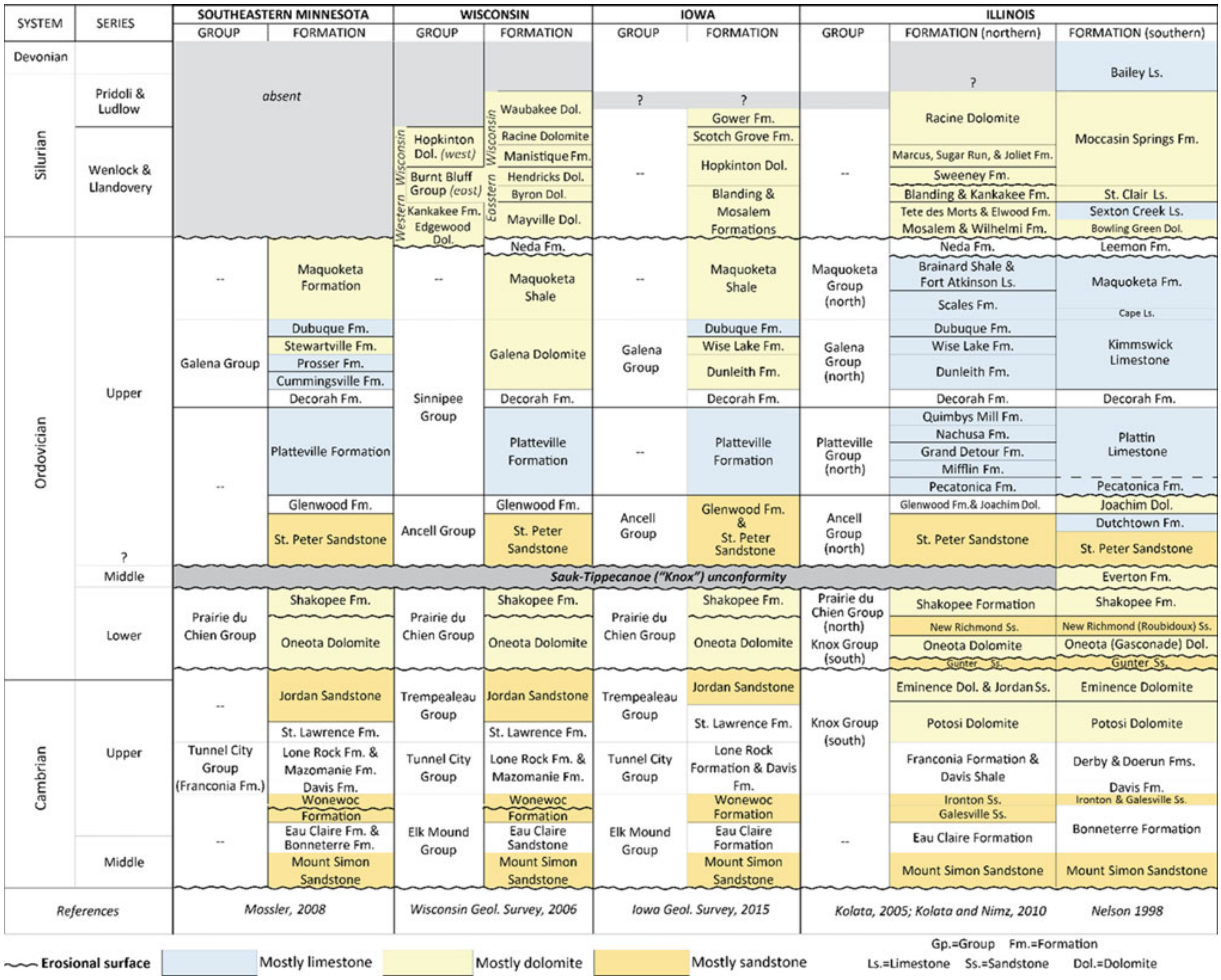

Fig. 1.6 Generalized correlation chart of the lower Paleozoic stratigraphy (Cambrian through Silurian) of Minnesota, Wisconsin, Iowa, and Illinois. References provided in the bottom row of the chart

exposed at this interval belong to the Knox Group, and thus this period of erosion is often referred to as the "Knox unconformity" (Fig. 1.6).

After this prolonged period of erosion, the surface was blanketed by the St. Peter Sandstone, an aeolian and near-shore marine sand that spread across much of the Upper Midwest (Mazzullo and Ehrlich 1987). The St. Peter Sandstone is composed of well-sorted, well-rounded, frosted, and pitted quartz grains that are weakly cemented by silica, carbonate minerals, and some iron oxides. As a result, the sandstone is friable where weathered, and often does not stand up well to erosion. Nonetheless, outcrops of this unit are frequently found, and may form low, rounded hills on the landscape. Breccia pipes have been found in the St. Peter where collapse has occurred into the underlying Prairie du Chien (Barr et al. 2008), possibly as a result of voids formed within the paleokarst surface at the Knox unconformity.

Atop the St. Peter Sandstone, shale of the thin and discontinuous Glenwood Formation was deposited, and above this, the Platteville Formation. Flaggy limestone layers of the Platteville Formation are conspicuous along the bluffs of the Mississippi River in the Twin Cities. Although the Platteville hosts few caves, several large caves in the cities of Minneapolis and St. Paul have formed within the St. Peter Sandstone and are capped with broad, flat ceilings held up by the Platteville (Brick 1997, 2009). In northern Illinois, the Platteville Group is subdivided into several formations based on the relative degree of argillaceous limestone and calcareous shale contained in the rock units and includes the Pecatonica, Mifflin, Grand Detour, Nachusa, and Quimbys Mill Formations. The Platteville is generally finer grained and thinner bedded than the rocks of the overlying Galena Group; however, the Pecatonica and Nachusa Formations resemble some parts of the

Fig. 1.7 Lower portion of the Shakopee Formation of the Prairie du Chien Group exposed in a roadcut near Chatfield, Minnesota (photo by D.H. Doctor)

Galena Group and may be mistaken for those younger rocks (Willman and Kolata 1978).

Overlying the Platteville is the Decorah Formation, the basal unit of the Galena Group. The Decorah is fossiliferous hosting well-preserved brachiopods, crinoids, bryozoans, and other fossils in a matrix of shale and fine-grained argillaceous carbonate. The Decorah Formation contains the well-known Deicke and Millbrig potassium-bearing bentonite beds that permit radiometric age determination and correlation with other rocks of this age across North America (Kolata et al. 1998). The Deicke has been dated using the $^{40}Ar/^{39}Ar$ technique on single grain biotite phenocrysts to 449 ± 2.3 Ma, and the Millbrig to 448 ± 2.0 Ma (Min et al. 2001).

The majority of caves in the UMV region, particularly in Minnesota, Iowa, and Wisconsin, are hosted by the carbonate rocks of the Galena Group that overlie the Decorah Formation. These rocks are generally more massive carbonate rocks than the older units. Significant zones of solutional development occurring along tensional fractures (joints) and bedding planes in these rocks have been documented throughout the UMV region. In Minnesota, solutional porosity tends to be concentrated at the contact between the Cummingsville and overlying Prosser Formations of the Galena Group (Runkel et al. 2003). Larger caves are also found in the Stewartville Formation of the Galena Group, including Mystery and Niagara Caves, two developed show caves in Minnesota. The Stewartville is primarily a dolostone and has distinctive *Thalassinoides* trace fossil burrows. Interbedded limestone and shale of the Dubuque Formation overlie the Stewartville in southeastern Minnesota, and these grade into thinner beds of shaly limestone.

Above the Galena Group is the Maquoketa Formation, a shaly dolostone in Minnesota and Iowa, mostly shale in Wisconsin, and shaly limestone in Illinois. Although some karst features are known in the Maquoketa in Minnesota, the unit becomes increasingly shale-dominated toward the east and is essentially a shale in Wisconsin such that it forms a regional aquitard.

1.3.3 Silurian System

Silurian rocks are generally poorly exposed throughout much of the UMV region due to glacial cover. The most significant karst within Silurian units occurs in the Door Peninsula of northeastern Wisconsin, parts of northeastern Iowa, and parts of northeastern Illinois (Fig. 1.2). The outcrops of Silurian strata occur on the edges of two large regional basins; thus, the Silurian strata are not well correlated between Iowa, Illinois, and Wisconsin. In eastern Wisconsin and northeastern Illinois, the Silurian rocks outcrop in an arcuate pattern that defines the western edge of the Michigan Basin (Fig. 1.2). In Iowa and northwestern Illinois, the Silurian rocks are found along the northwestern edge of the Illinois Basin. The Silurian strata were extensively dolomitized during diagenesis.

In Door County, Wisconsin, the Silurian is primarily represented by the rocks of the Burnt Bluff Group. Soderman and Carozzi (1963) reported that “the Burnt Bluff Group of

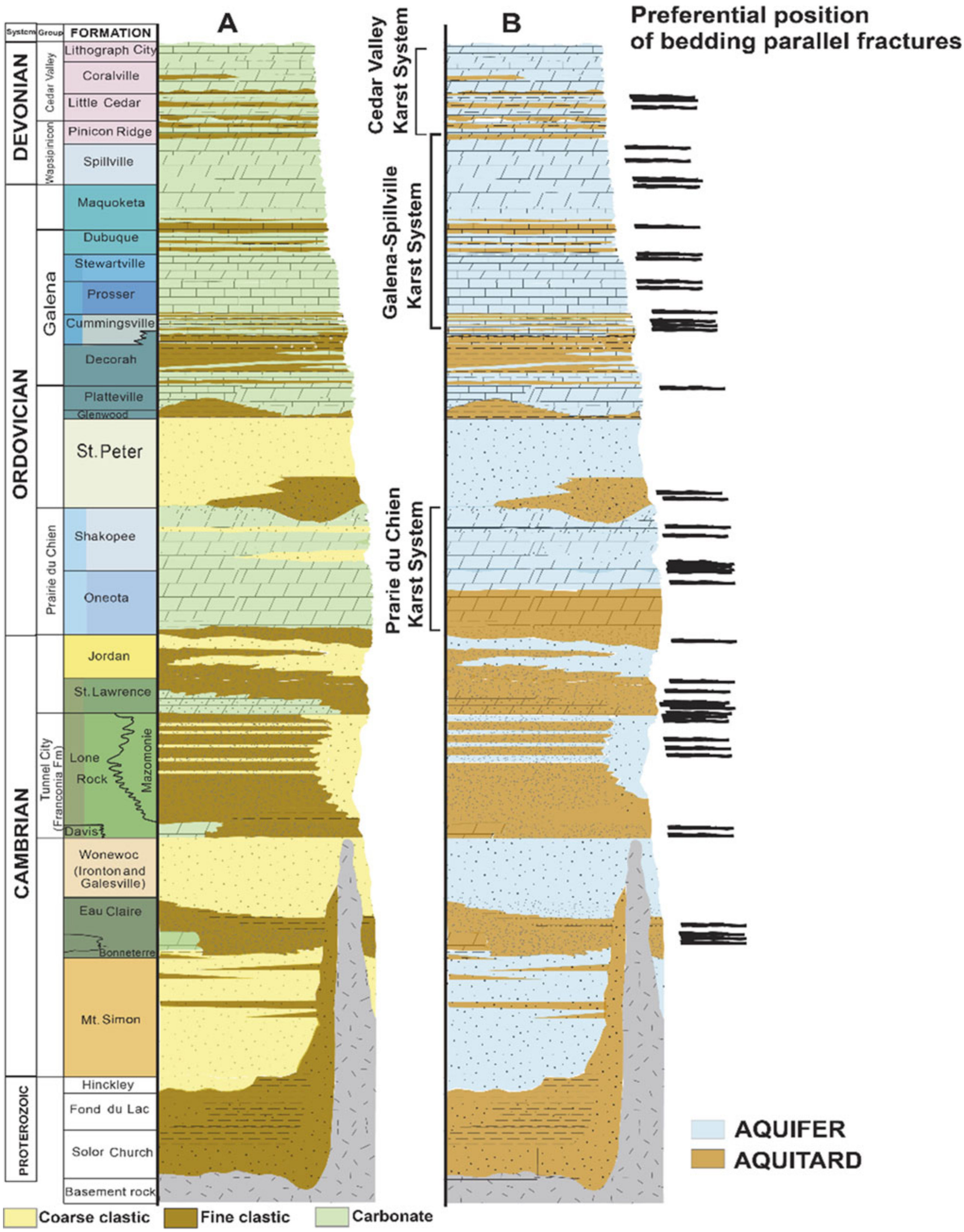

Fig. 1.8 Paleozoic bedrock stratigraphy in southeastern Minnesota. Column A illustrates the lithostratigraphic components and column B illustrates the hydrogeologic units. Also shown are stratigraphic positions of the three major karst systems and preferential positions of bedding parallel fracture networks (from Runkel et al. 2014)

Wisconsin consists of approximately 30 m (100 ft) of predominantly thin-bedded dolomite and some partings and thin beds of clay, is apparently conformable with the underlying Mayville Dolomite and the overlying Manistique Group, and correlates approximately with the Burnt Bluff Group of Michigan and the central part of the Kankakee Dolomite of Illinois" and that "subdivision of the Burnt Bluff Group in Michigan is based on paleontological data (Ehlers and Kesling 1957), but a lack of fossils in the sections studied in Wisconsin precludes the use of this method."

Karst features in the peninsula of Door County, Wisconsin, occur in several formations (Johnson and Stieglitz 1990) but primarily on the western side of the peninsula within the Byron and Hendricks Formations of the Burnt Bluff Group (Rosen and Day 1990). The Maquoketa Shale underlies the Silurian dolostones and serves as a regional aquitard (Rayne et al. 2001).

Tecumseh Cave, one of the longest known caves in Wisconsin with 740 m (2,428 ft) of explored passages, is a solutional cave on the Door Peninsula; the second longest cave on the peninsula, Dorchester Cave, is formed in the Manistique Formation, but is thought to have formed through gliding of a large rock block under glacial stresses (Johnson and Stieglitz 1990). Fracture orientations in Door County are likely controlled by the present-day stress field or past stress fields associated with the Alleghanian and Ouachita orogenies (Underwood et al. 2003).

Silurian strata in the Lincoln Hills region of southern Illinois host karst features primarily within the Sexton Creek Limestone (Panno et al. 1997, 2020 this volume). To the northwest in the Driftless Area of Illinois and Iowa, the Silurian units that host karst features include the Mosalem, Tete des Morts, Blanding, and Hopkinton Formations, with most sinkholes occurring in the dolomitic Hopkinton Formation (Panno et al. 1997; Brick 2004). In northeastern Illinois, most of the bedrock at the surface is Silurian in age and is located on the northeast flank of the Kankakee Arch, which forms the division between the Illinois Basin and the Michigan Basin. Numerous karst features occur within Silurian rocks in this part of Illinois, particularly within the Racine Dolomite. Much of the bedrock surface is buried beneath glacial till and other sediments but would seem to host an intrastratal karst. Bretz (1940) reported a cave intersected by quarry activities in the Joliet Dolomite as having slumped fill of Pennsylvanian shale from an overlying unit, and concluded "that not all buried 'sink holes' at the contact of a limestone and an overlying shale formation are relicts of a former karst topography, that some such 'sinks' may develop de novo or may become greatly enlarged by solutional removal of limestone after the shale was deposited" (Bretz 1940, p. 1) (Fig. 1.9).

1.3.4 Devonian System

Rocks of the Lower Devonian are only encountered in southern Illinois; lack of deposition or erosion caused an absence of Lower Devonian rocks in Minnesota, Iowa, and Wisconsin. The Lower Devonian rocks are sometimes referred to as the "Helderbergian" sequence in Illinois (Willman et al. 1975) and correlate to the well-known karst-bearing rocks of the Helderberg Group in the eastern states of New York, New Jersey, Pennsylvania, Maryland, Virginia, and West Virginia. In the Shawnee Hills region of southern Illinois, a few sinkholes and caves are found within the Lower Devonian Bailey and Backbone Limestones, and in the Middle Devonian Grand Tower and Lingle Limestones of the western Shawnee Hills (Panno et al. 1997, 2020, this volume).

Middle Devonian carbonates that host karst features occur primarily in strata of the Wapsipinicon and Cedar Valley Groups in southeastern Minnesota, northeastern Iowa, and northwestern Illinois. In Wisconsin, Devonian carbonates of the Thiensville and Milwaukee Formations crop out at the surface adjacent to Lake Michigan in only small areas (Fig. 1.2).

In Minnesota, the Devonian carbonates and shales of the Wapsipinicon and Cedar Valley Groups are the first bedrock under the southwest corner of Fillmore County and most of Mower County in Minnesota (Mossler 1998a). However, in a broad northwest/southeast band across Mower County and the southwestern corner of Fillmore County, the Devonian bedrock is covered by more than 15 m (50 ft) of pre-late Wisconsinan glacial drift and younger alluvium (Mossler and Hobbs 1995; Mossler 1998b; Meyer and Knaeble 1998).

The Middle Devonian Spillville Formation lies above a regional unconformity that sits atop the Upper Ordovician Maquoketa Formation. Together with the Galena Group rocks, the Spillville forms a regionally continuous horizon of karst development, the Galena-Spillville karst (Runkel et al. 2014; Fig. 1.8). Surface karst features are present in Devonian bedrock in western Fillmore County (Witthuhn and Alexander 1995), as well as along the eastern edge of Mower County, especially in and around Le Roy (in the Lithograph City Formation) in the southeastern corner along the Upper Iowa River and in Mower County along the Cedar River and its tributaries (in the Little Cedar Formation) around and south of Austin, Minnesota (Green et al. 2002). The surface karst features include sinkholes, springs, caves, and a blind valley. For example, Junk Hole Cave is located just north of Cherry Grove in Fillmore County, in the lower part of the Spillville Formation (Brick 1989). The largest blind valley in Minnesota, the York Blind Valley, in Sect. 21 of York Township, is also in the Spillville Formation.

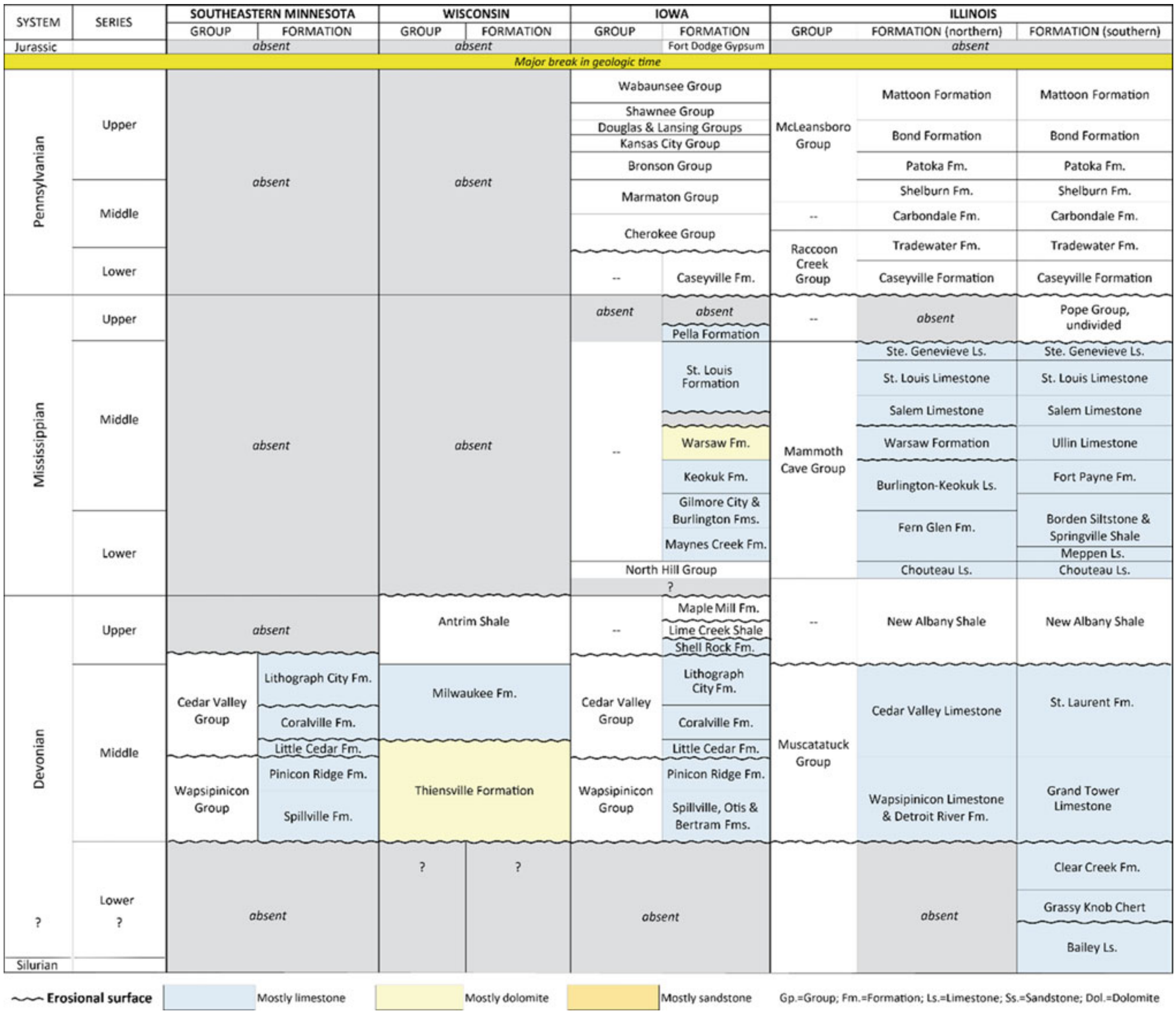

Fig. 1.9 Generalized correlation chart of the upper portion of the Paleozoic (Devonian through Pennsylvanian) stratigraphy in Minnesota, Wisconsin, Iowa, and Illinois. References provided in the bottom row of the chart in Fig. 1.6

The topography over Devonian bedrock in Minnesota is relatively flat and few natural outcrops exist. Several aggregate quarries mine Devonian carbonates and the walls of those quarries reveal the carbonates to be highly jointed with well-developed horizontal bedding partings. While the land surface is relatively flat, the alluvium/bedrock surface is highly irregular at the few meter scales with solution-produced cutters and grikes (Green et al. 2002). The sinkholes and springs in Devonian strata in western Mower County around and south of Austin are the northern end of a larger array of sinkholes extending south-southeast across Iowa. The sinkholes and springs around Le Roy in the southeastern corner of Mower County are the northern end of a second large array of sinkholes extending south into Iowa.

1.3.5 Mississippian System

The Mississippian strata of North America host the richest development of caves and karst in the conterminous United States (Palmer and Palmer 2009). However, in the UMV region, rocks of Mississippian age are exposed only in southwestern Illinois and in Iowa. These rocks host the majority of well-developed surface karst and caves in Illinois, particularly within the Shawnee Hills karst area (Panno et al. 1997).

Underlying the Mississippian strata in Illinois and Iowa is the Devonian New Albany Shale. These shales were rich in organic matter and provided the source rock for petroleum reservoirs contained within the overlying carbonate units.

Gypsum-bearing evaporite deposits are known within both the Illinois Basin and Forest City Basin (Fig. 1.3).

Several units bearing sinkholes and caves in Illinois and Iowa include the Salem, St. Louis, and Ste. Genevieve Limestones, which are the same units that host Mammoth Cave in Kentucky. Sinkholes are also found within the Glen Dean and Menard Limestones of the overlying Pope Group. For a detailed discussion of karst development in the Mississippian strata in Illinois, see Panno et al. 2020 (this volume).

1.3.6 Pennsylvanian System

Pennsylvanian strata of south-central Iowa commonly exhibit repetitive depositional cycles consisting of limited amounts of carbonate units intercalated with siliciclastic and coal-bearing sediments. Carbonates are known to occur throughout much of the Pennsylvanian section, but particularly within the Bronson and Kansas City Groups.

Due to the thin and often shaly nature of these beds, carbonates in the Pennsylvanian strata are unlikely to form caves, or even to result in sinkholes at the land surface. However, solutional voids within these units are known to contain paleokarst features that may become excavated and convey groundwater at elevated velocities. Therefore, these karst features may be of interest for water resource management and protection.

For example, a 22 foot (6.7 m) thick section of the Bethany Falls Member of the Swope Formation of the Bronson Group was measured along the south high wall at the Decatur City Quarry, Decatur County and was described as being "heavily karsted," possibly with solutionally formed root holes (Pope and Marshall 2010). Apparently, this was a paleokarst surface, as the unit is described as having an irregular contact with the overlying Galesburg Shale (Fig. 1.10).

1.4 Paleokarst

The development of karst within the Paleozoic strata is partially controlled by periods of surface exposure and erosion that interrupted the deposition of the sediments. These periods are gaps in the geologic depositional record when sediments were either not deposited, or deposited and subsequently removed by erosion before the overlying sediments were deposited. More importantly, these unconformities and lesser disconformities within the stratigraphy of the UMV region have permitted development of paleokarst horizons in the geologic past. The paleokarst resulted from the exposure of the carbonate formations at the land surface, before, during, and after the formations were buried by overlying sediments. Karst processes have been episodically modifying these Paleozoic strata throughout their geologic history (Hedges and Alexander 1985; Kluessendorf et al. 1988).

A major episode of paleokarst formation is the Sauk-Tippecanoe megasequence boundary, represented by the St. Peter Sandstone overlying the carbonate rocks of the Prairie du Chien Group. This sequence boundary is correlated to the Knox unconformity of eastern North America. Paleokarst at this boundary is visible in outcrops below Bridal Veil Falls at Pikes Peak State Park in Clayton County, Iowa where the St. Peter Sandstone fills a paleokarst basin in the underlying dolomite of the Prairie du Chien Group (McKay 1996).

Lower in the Ordovician Prairie du Chien (OPDC) section near the boundary between the Oneota Dolomite and the overlying Shakopee Formation is an extensive, regionally mappable karst weathering zone (Fig. 1.11). This "OPDC High Transmissivity Zone" (Tipping et al. 2006) is a major conduit for long distance, rapid groundwater movement in the Prairie du Chien (Fig. 1.9). Many of the sinkholes, caves, and other karst features are reactivating and modifying much older paleokarst features. For example, three of the roughly 20 wastewater treatment lagoons built in the 1970s and 1980s to handle municipal waste from small towns in southeastern Minnesota catastrophically failed when sinkholes opened and drained the lagoons. All three of the lagoon failures, Altura in 1974 and 1976 (Alexander and Book 1984), Lewiston in 1991 (Jannik et al. 1992) and Bellechester in 1992 (Alexander et al. 1993) were constructed directly above the OPDC High Transmissivity Zone. The sinkholes apparently drained into the paleokarst horizon.

In Illinois, several zones of paleokarst development have been documented in rocks of varying ages (Illinois Paleokarst fills: https://www.kenig-ogl.org/paleokarsts-and-sediment-fills.html, accessed Feb. 20 2020). Paleokarst in Illinois contains fossil pollen and plant remains of Pennsylvanian age (Plotnick et al. 2009). The caves have been discovered during quarry operations in the northeastern part of the state, primarily in Silurian and Devonian strata. Bretz (1940) described solutional cavities in the Silurian Niagara Dolomite in a quarry near to Joliet, Illinois. In addition, a significant and widespread paleokarst surface has been recognized at the top of the Silurian Kankakee Formation in northeastern Illinois, and extending into southeastern Wisconsin over an area of $\sim$10,000 km^2 ($\sim$3,860 mi^2) (Kluessendorf and Mikulic 1996).

Evidence for a Pennsylvanian karst surface on top of Silurian dolostone in northeastern Illinois has been described by Bretz (1940). Sediment-filled paleokarst caves were discovered in 2004 in the Central Limestone Company Quarry, Kendall County, Illinois (Plotnick et al. 2008). The host

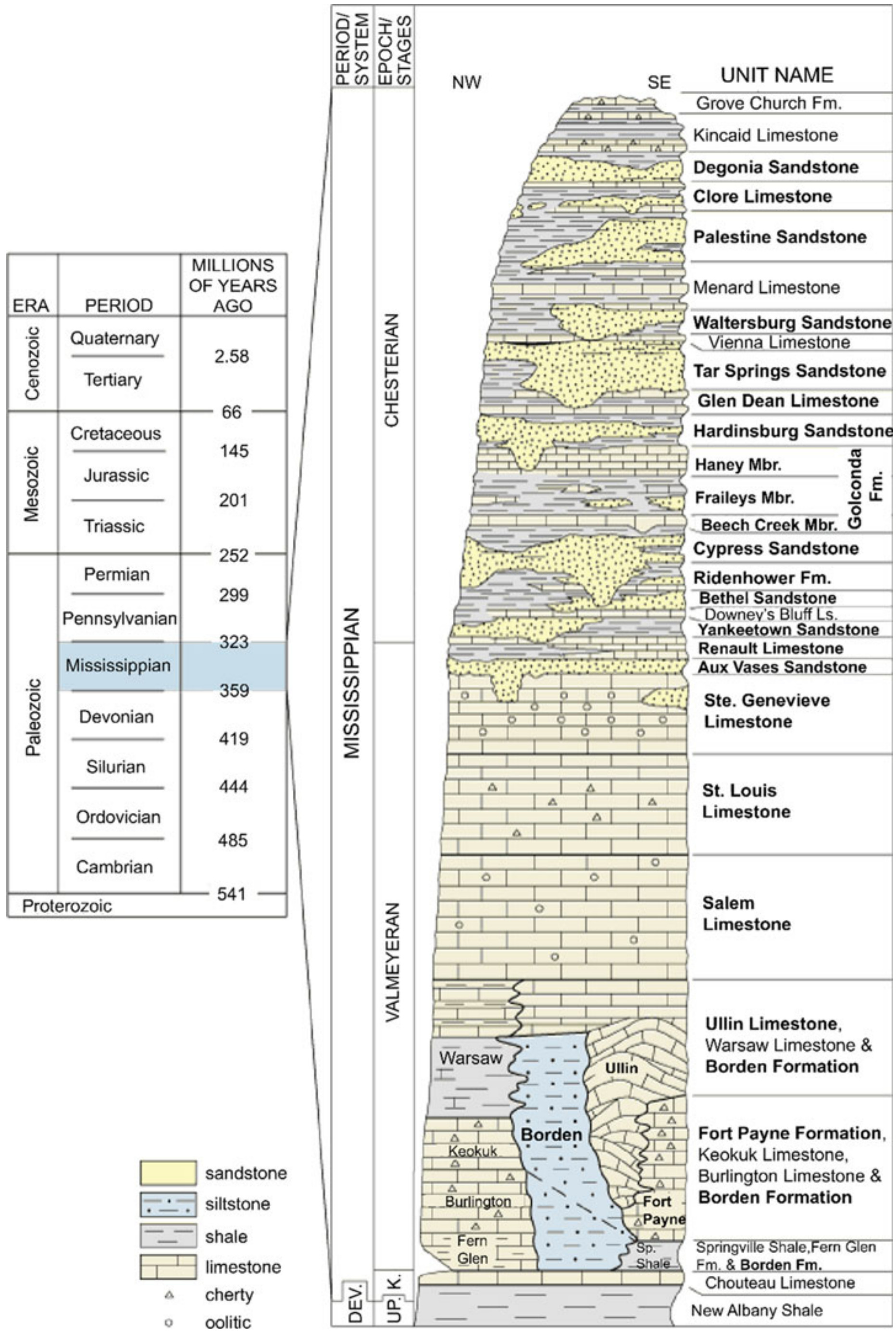

Fig. 1.10 Mississippian stratigraphy of southern and western Illinois. Units that have produced oil are shown in bold type. The base of the Fort Payne Formation is approximately equivalent in time to the base of Keokuk Limestone (dashed line) (Kolata and Nimz 2010). DEV, UP = Upper Devonian, and K = Kinderhookian (from the Illinois State Geological Survey: https://isgs.illinois.edu/outreach/geology-resources/mississippian-rocks-illinois)

rocks are Upper Ordovician limestones of the Dunleith Formation and Galena Group. These caves contain sediments of Pennsylvanian age. The sediment fills apparently represent a speleogenetic process via paragenesis, whereby the sediments in-filled passages nearly contemporaneously with the passage formation. Fossil pollen and plant remains of early North American conifers are contained in the fills, and remains of a scorpion were also found (Plotnick et al. 2015). These paleokarst features appear to be correlative to paleokarst that formed after deposition of the Kaskaskia, and thus likely formed in the latest Mississippian or earliest Pennsylvanian (Plotnick et al. 2008).

In northwestern Illinois, paleokarst features are known from Devonian limestones of the Rock Island area (Leary 1981; Leary and Trask 1985). A Devonian paleokarst surface has also been recognized at the top of the Thiensville Formation in eastern Wisconsin (Kluessendorf et al. 1988).

In Iowa, paleokarst occurrences have been documented in several portions of the eastern part of the state. For example, the Linwood Mine in Scott County contains mineralized

Fig. 1.11 OPDC high transmissivity zone: large solution cavities aligned along the Oneota Dolomite-Shakopee Formation contact, Wabasha County, Minnesota. Person in lower left for scale (Runkel et al. 2014)

zones of paleokarst cavities (Garvin 1995). In addition, numerous paleokarst features with fills of Pennsylvanian sediment have been documented within the Devonian Cedar Valley Group in the Klein and Conklin quarries near Iowa City (Marshall and Witzke 2010).

1.5 MVT Ore Mineralization

Mississippi Valley Type (MVT) lead and zinc ore deposits are associated with the Paleozoic carbonates of southwestern Wisconsin, northwestern Illinois, and northeastern Iowa. The most comprehensive work describing the geologic context of the deposits was by Heyl et al. (1959). The ore minerals within the deposits are galena (PbS) and sphalerite (ZnS), with lesser amounts of iron and copper sulfides; fluorite, barite, calcite, and dolomite are gangue minerals found in abundance. The ore deposits of the UMV are hosted by Ordovician rocks, primarily immediately overlying the St. Peter Sandstone. The Ordovician Platteville and Galena Groups are the main intervals of rocks that host the deposits, although some mineralization also occurs in the Prairie du Chien Group and in the lower Silurian rocks in northeastern Iowa (Heyl et al. 1959). For example, the Thompson-Temperly mine located in Lafayette County, Wisconsin, yielded abundant ore from the Quimbys Mill Member of the Platteville Formation, the Decorah Formation, and the lower part of the Galena Group (Heyl et al. 1959; Hatch et al. 1986).

Several studies have shown that the ore fluids were derived mainly from evaporated seawater (Leach et al. 2010). The prevailing model for ore emplacement is the movement of basinal brines through the platform carbonates by tectonic forcing during major orogenic events. Age dating of sphalerite using $^{87}Rb/^{86}Sr$ radiometric methods has supported this idea, and some sphalerite ores in Wisconsin have been dated to 270 ± 4 Ma and supported by paleomagnetic data (Pannalal et al. 2004). This age places ore emplacement during the Alleghanian orogeny, when the Appalachian and Ouachita Mountains were uplifted. Uplift of the Ouachita Mountains is thought to have been a potential driver for migration of deep basinal ore-bearing brine fluids to the north into the UMV where economic minerals were ultimately deposited (Appold and Garven 1999; Appold and Nunn 2005).

Deposition of lead and zinc sulfide ores is accompanied by carbonate mineral dissolution and precipitation of associated accessory and gangue minerals. Certain accessory minerals such as fluorite and barite are often economically recovered in addition to the lead and zinc sulfides; in 1965, fluorite mining was a multi-million dollar per year industry in Illinois and fluorite became the state mineral of Illinois (Illinois Geological Survey 2019).

The dissolution of the carbonate rock is evident in some caves intercepted during mining activities that contain wall coatings of these ore minerals (e.g., Garvin and Ludvigson 1993). A detailed description of the history of mining of these ores in the UMV region and associated karst development is provided by Dockal (2020), Chap. 7, this volume.

1.6 Evaporite Deposits

Deeply buried basin sediments host evaporites in the form of gypsum and anhydrite in the subsurface of Iowa and Illinois. In southern Iowa, these deposits occur within the Forest City Basin in the Silurian and Devonian Cedar Valley and Wapsipinicon Groups (Witzke et al. 1988). In addition to these deposits occurring in the same units within the Illinois Basin, gypsum occurs in the Mississippian strata within the St. Louis Limestone (Saxby and Lamar 1957).

The Fort Dodge Gypsum is perhaps the most well-known evaporite of the UMV region. Initially thought to be Cretaceous (Keyes 1893; Wilder 1903), the age of these deposits is now known to be Jurassic (Clark 2014). The thickness of the gypsum deposits is highly variable and ranges from 3 of 4 feet to more than 30 feet, with the average thickness being about 16 feet (Keyes 1893). The gypsum beds are unconformably overlain by glacial till and rest unconformably upon Pennsylvanian coal measures. The Fort Dodge Gypsum has been mined for many decades, and some quarries are still active (Clark 2014). A comprehensive discussion of the Fort Dodge Gypsum is provided by Lace et al. (2020) (this volume) on the karst of Iowa.

1.7 Pleistocene Glaciation

Several episodes of glacial ice sheet advance and retreat occurred in the Upper Midwest during the Pleistocene Epoch, from 2.58 million years to about 11,700 years ago, after which the earth warmed to its present state of interglacial climate (Fig. 1.12). The geologic record of these glacial episodes is contained in the sediments left behind once the ice sheets retreated.

Most, but not all, of the areas in the four states of the UMV region have been repeatedly covered by continental glaciation during the Pleistocene (Fig. 1.12). The geochronology of the most recent late Wisconsinan ice sheets is well established by various age dating techniques. The southern extent of the Wisconsinan ice cover is shown by the red line in Fig. 1.13. Multiple glacial cycles have profoundly modified the pre-Pleistocene karst landscapes and subsurfaces. Sinkholes and some caves were filled with glacial till. The upper portions of the epikarst were scraped off by the ice during the glacial advances leaving relatively level, flat carbonate rock surfaces in many areas. Enormous volumes of carbonate and non-soluble tills were left on top of the karst landscapes in other areas during the retreat of the glacial ice. Many cubic kilometers of meltwater flowed over and through the karst areas. The direction and magnitude of groundwater gradients in the karst repeatedly changed as the glaciers advanced and

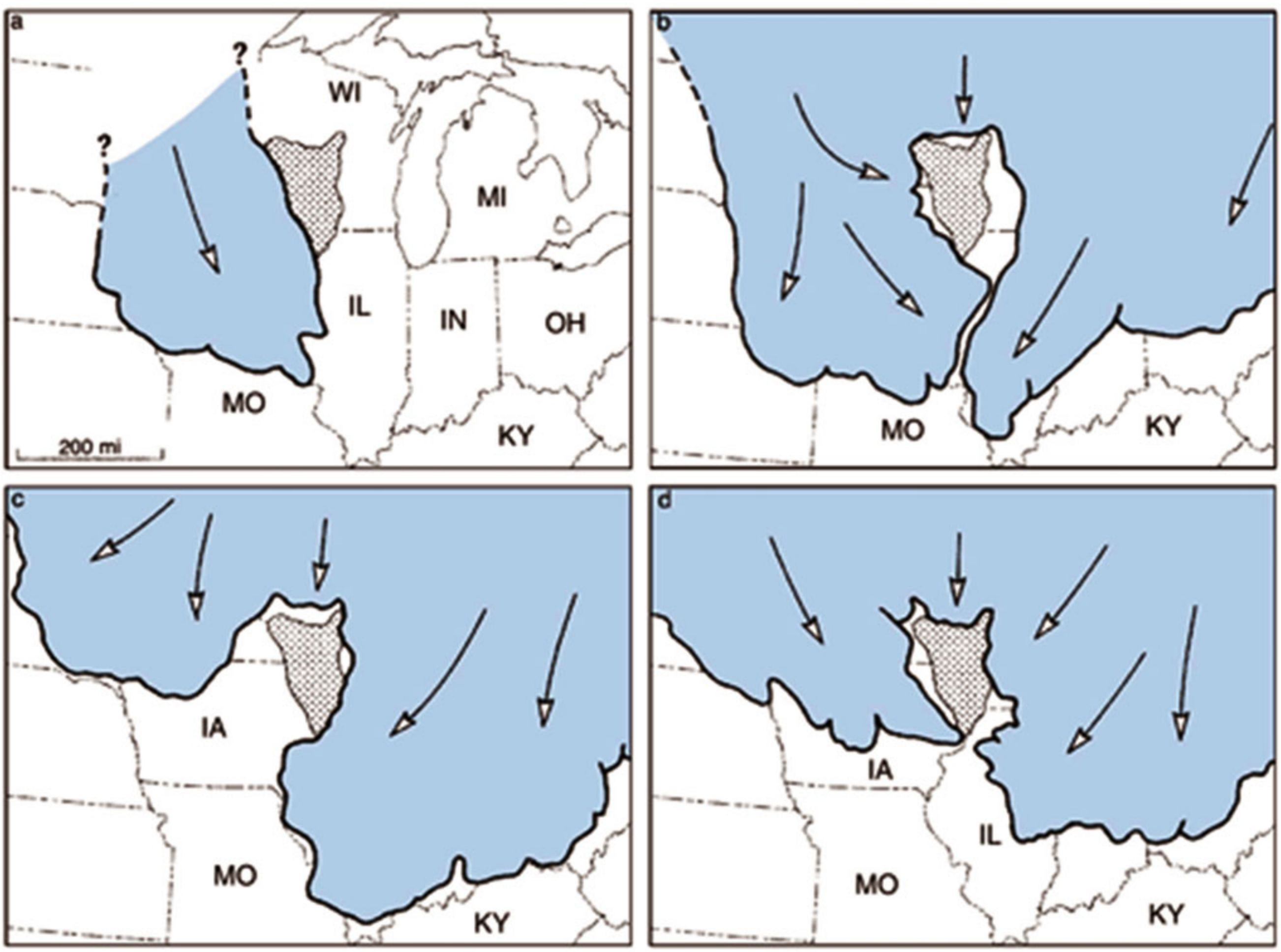

Fig. 1.12 Maximum extent of **a** early Pre-Illinois glacial episode (~1,000,000 years age); Driftless Area shown by stippled pattern; arrow indicates direction of ice movement; **b** late Pre-Illinois glacial episode (~600,000 years ago); **c** Illinois glacial episode (~250,000 years age); **d** late Wisconsin glacial episode (~22,000 years ago) (from Illinois Geological Survey: https://isgs.illinois.edu/outreach/geology-resources/glaciers-smooth-surface, accessed Feb 20 2020)

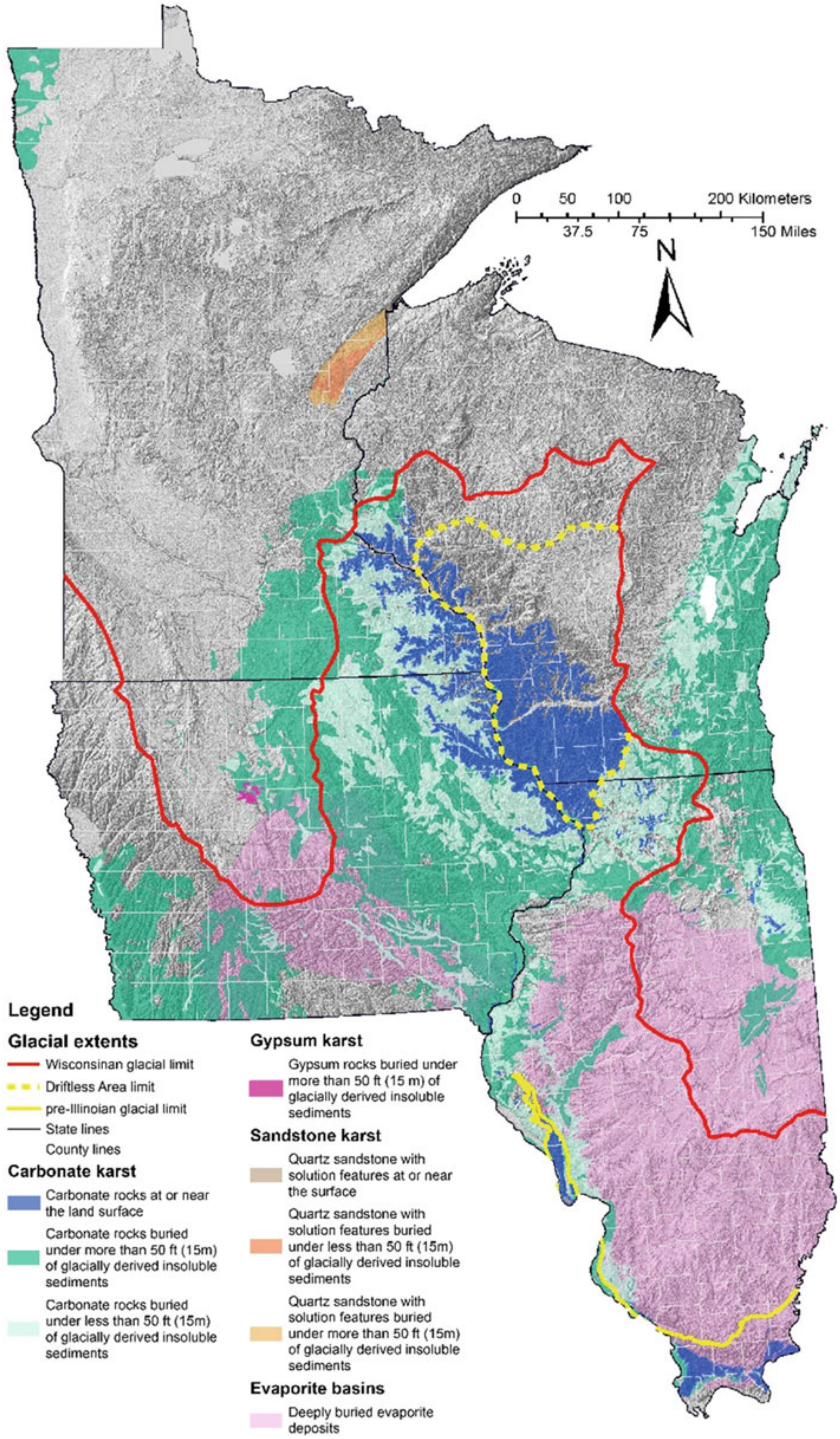

Fig. 1.13 Soluble bedrock units of Minnesota, Iowa, Illinois, and Wisconsin shown according to rock type and thickness of glacial sediment cover. Evaporite rocks deeply buried within basin are also shown. The limit of glacial ice advance during the last (Wisconsinan) ice age is depicted with the red line. Data from Weary and Doctor (2014)

retreated. The meltwater and those changing gradients moved enormous volumes of outwash through the systems, resulting in what have been termed glacially “deranged” karst systems (Ford and Williams 2007).

Deep bedrock valleys incised by ancient rivers during ice sheet retreat lie buried beneath glacial sedimentary cover that may be hundreds of meters deep. The major exception is the Driftless Area enclosed by the dashed yellow line in

Fig. 1.14 An outcrop of the Galena Group in southeastern Minnesota located to the west of the Driftless Area. Note the lack of well-developed epikarst; despite the lack of glacial sediments atop the bedrock, this area was impacted by glaciation in the Pleistocene. North-northwest dipping systematic joints cutting across near-horizontal bedding partings; these fractures likely resulted from stresses applied during the Alleghanian orogeny and were likely enhanced by stress-release after retreat of glacial ice. Photo taken along County Hwy 5 between the villages of Fillmore and Wyckoff in Fillmore County (photo by D.H. Doctor)

Fig. 1.13 in southwestern Wisconsin and the extreme northwestern corner of Illinois. This area has apparently never been covered with glaciers (the southern tip of Illinois may also have never been covered by glaciers). This Driftless Area has been influenced by the Pleistocene glacial advances and retreats. During the glacial maximum, permafrost, loess deposition, and other periglacial processes affected the Driftless Area. During ice melt-backs, glacio-fluvial sediments washed through parts of the Driftless Area.

Hobbs (1999) speculated: "The Driftless Area occupies the eastern part of the Paleozoic Plateau, a relatively high area of Paleozoic sedimentary bedrock that is generally permeable and is deeply dissected by the Mississippi River and its tributaries. Bedrock of the Paleozoic Plateau acted as a giant sieve that was able to dewater the base of advancing ice. The exposed bedrock created pinning points that inhibited ice advance across the Paleozoic Plateau. Ice therefore flowed around the eastern and western margins of the Driftless Area and continued its advance as far as southern Illinois and central Missouri." See also Iannicelli (2010) and references therein.

The area between the eastern lateral moraine of the late Wisconsinan Des Moines lobe and the Mississippi River in southeastern Minnesota and northeastern Iowa is too often referred to as part of the Driftless Area in scientific and popular usage (Fig. 1.13). However, the bedrock surface had been scraped off by ice such that there is little to no development of a thick epikarst horizon (Fig. 1.14). Discontinuous sheets of multiple weathered tills are also mapped in the surficial geology of the area. Meter-scale glacial erratics of igneous and metamorphic cobbles abound in the landscape indicating that the area was glaciated in the pre-Illinoisan Pleistocene (Fig. 1.15).

1.8 Age of the Karst Landscape

"How old is the cave?" is a question one often hears while exploring underground passages. The answer is usually not simple, nor easily determined. While an upper bound on the age of a cave is determined by the age of the bedrock and a lower bound by the age of the oldest deposits within the cave, the actual age of a cave is somewhere in between. The timing of the creation of a cave void is determined by the processes that control the overall evolution of the karst landscape that hosts the cave.

Similar to caves, we gain clues about the age of a karst landscape based on the oldest deposits that can be found within the "pockets" of the karst itself, the sinkholes. Sinkholes can be excellent repositories of geologic information, often containing deposits that have survived intact and in place for thousands of years, and occasionally for millions of years. In the Upper Midwest, the processes that formed the karst span millions of years, and some sinkhole deposits are similarly as old. Although the preservation of such old deposits is quite sparse, when discovered they provide invaluable insight into the age of the landscape.

For example, Sloan (1964) described the informal Iron Hill Member of the Cretaceous Windrow Formation in southeastern Minnesota as being a "heterogenous deposit of limonite (dominantly goethite) and admixed chert fragments, silt and clay. It forms bouldery, irregular masses, without noticeable bedding or other sedimentary structures, and contains local residual blocks of older carbonate beds. Typically, it occurs on a karst topography, primarily as fillings in enlarged joints and sinkholes or caves." The age of the formation is inferred from fossils of leaf imprints, carbonized wood, and shark teeth. Sloan (1964) also reported the presence of a Cretaceous fossil shark tooth found in place within a sinkhole pit that had been mined for clay and iron ore at Bellechester. These findings led to acknowledgement of preservation of some karst features within the landscape dating back to the Cretaceous.

In Missouri, a remarkable find in Bollinger County was unearthed in the early 1940s by the Chronister family while they were digging for a cistern in clay deposits that had filled a sinkhole. A geologist from the Missouri Geological Survey, Dan R. Stewart, who happened to be interested in such deposits was led to the site. The family had found and saved several bones, which were later described by Charles Gilmore of the Smithsonian Museum of Natural History as being