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# *Karst mapping in the United States: Past, present, and future*

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## ABSTRACT

**The earliest known comprehensive karst map of the entire United States was published in 1969, based on compilations of William E. Davies of the U.S. Geological Survey (USGS). Various versions of essentially the same map have been published since. The USGS published new digital maps and databases in 2014 depicting the extent of known karst, potential karst, and pseudokarst areas of the United States, including Puerto Rico and the U.S. Virgin Islands. These maps are based primarily on the extent of potentially karstic soluble rock types, and rocks with physical properties conducive to the formation of pseudokarst features. These data were compiled and refined from multiple sources at various spatial resolutions, mostly as digital data supplied by state geological surveys. The database includes polygons delineating areas with potential for karst tagged with attributes intended to facilitate classification of karst regions. Approximately 18% of the surface of the 50 United States is underlain by significantly soluble bedrock. In the eastern United States, the extent of outcrop of soluble rocks provides a good first approximation of the distribution of karst and potential karst areas. In the arid western states, the extent of soluble rock outcrop tends to overestimate the extent of regions that might be considered as karst under current climatic conditions, but the new data set encompasses those regions nonetheless. This database will be revised as needed, and the present map will be updated as new information is incorporated.**

## INTRODUCTION

Numerous environmental and engineering problems arise in areas where geologic substrates are subject to solution and erosion, which can generate voids in the subsurface. Such areas are collectively known as karst. The term karst has traditionally been used to refer solely to regions of exposed soluble bedrock with an abundance of surface landforms such as sinkholes, sinking streams, and springs that reflect the presence of subsurface voids (caves; Ford and Williams, 2007). However, in the last few decades, a distinction has been drawn between karst features that reflect surficial (epigenic) processes and deep-seated (hypogenic) solutional processes that result in bedrock voids (Palmer, 1991). Consequently, usage of the term karst has broadened, as recognition of karst features existing deep in the subsurface in numerous environments has gained greater attention (Klimchouk, 2007).

Karst or pseudokarst[1] features occur in each of the 50 United States. About 18% of the United States is underlain by soluble

[1]We apply this term to the broad categorization of karst-like geomorphic features that do not involve solutional processes, while recognizing that some debate exists regarding its appropriate usage (e.g., Eberhard and Sharples, 2013).

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rocks with potential for karst development. These terrains are characterized by unique vulnerabilities and hazards, as well as hydrologic, biologic, abiotic, and recreational resources. Characterizing different karst types and accurately delineating areas that may contain karst features are useful pursuits in order to inform and guide policies for management of these diverse resources and potential hazards. To this end, scientists in the United States have been compiling and revising karst maps with national extent since the 1960s.

### Karst Maps of the United States

The earliest published depiction of the extent of karst features across the United States was a map showing the density of caves in limestone by Moore and Sullivan (1964). This map was followed by publication, a few years later, of a map of karst lands in the United States by Stringfield and LeGrand (1969). Their map, based partially on data provided by William E. Davies of the U.S. Geological Survey (USGS), delineated karst areas and areas of carbonate and sulfate rocks at or near the surface in the contiguous 48 states, discriminating between areas underlain by soluble rocks with and without known karst features. In addition, the map was divided into four broad "groundwater regions," reflecting awareness of the importance of climate and general geologic setting on the development of karst regions.

Subsequent to publication of the Stringfield and LeGrand (1969) map, the USGS released maps of *Karstlands* and *Cavern Areas* as part of the National Atlas series (Davies, 1970). These maps covered all 50 states at a scale of 1:17,000,000. The *Karstlands* map showed areas of limestone, dolomite, gypsum, and salt terrains with reported surficial karst features. The map also included terrains underlain by lava, sediments, and granitic rocks with reported pseudokarst features. The various karst and pseudokarst terrains were characterized by types of karst features and generalized physiographic setting. In an attempt to differentiate between solutional and nonsolutional features, Davies used the term "doline" for closed depressions in terrains of soluble rocks, but "sinkhole" in pseudokarst areas. No attempt was made to differentiate karst areas on the basis of climate or other factors. Based on current knowledge, many of the karst areas on this map were either overrepresented or underrepresented. For example, karst areas in the northern part of the southeastern Atlantic Coastal Plain were over represented, while the extent of karst in the Great Valley of northern Virginia, Maryland, and Pennsylvania was underrepresented.

The map of cavern areas of the United States by Davies (1970) was a dot map indicating the locations of caves, or groups of caves. The map differentiates caves in four classes of rock type: (1) carbonates, (2) gypsum, (3) lava, and (4) other, relatively insoluble rocks. While portraying the known distribution of cave areas across the United States in 1970, this data set is now out of date. Thousands of additional caves and cave areas, particularly in the western United States, have been discovered and documented since 1970 (for regional examples, see Palmer and Palmer, 2009). A more recent dot map indicating the number of caves per county across the United States was published by Culver et al. (1999), and it was accompanied by a map of the number of cave-adapted animal species (stygobites and troglobites) per county. The precise locations of caves on these maps were obscured by randomly locating the dots within the spatial extent of the counties from which they were reported (Culver et al., 1999). The Federal Cave Resources Protection Act of 1988 prohibits federal agencies tasked with mapping geologic or geographic features from providing precise locations of significant caves on published maps, thus necessitating some degree of obfuscation in the representation of caves on maps of karst areas.

In 1984, the USGS published another national-scale map in the National Atlas series titled *The Engineering Aspects of Karst* (Davies et al., 1984). This map shows karst and pseudokarst areas at a scale of 1:7,500,000. Karst areas on the map are characterized by abundance and extent of fissures and caves and further subdivided by geologic setting, including general rock type, metamorphism, and extent of structural deformation. Generalized areas of extensive, historical karst-related subsidence are also outlined on this map. Pseudokarst terrains in lava and sedimentary rocks are also shown and are termed "features analogous to karst." This map was later digitized by the USGS and published as an online Open-File Report (Tobin and Weary, 2004).

A map of karst in the United States, somewhat simplified, updated, and revised from the portrayal of Davies et al. (1984), was published by Veni and others in 2001 (Veni et al., 2001). This map shows karst terrains in carbonate and evaporite rocks, and pseudokarst in volcanic rocks and unconsolidated material. Because of its graphic clarity, reproductions of this map are often used as the introductory location figure for presentations and reports on karst in the United States.

In recent years, Ken Johnson, of the Oklahoma Geological Survey, and other researchers have concentrated specifically on studies of karst in evaporite rocks of the United States. See various papers in Johnson and Neal (2003) and Land et al. (2013) for examples of this work.

## RECENT KARST MAPPING BY THE U.S. GEOLOGICAL SURVEY

The USGS, in cooperation with the National Cave and Karst Research Institute (NCKRI), the National Speleological Society (NSS), and the Association of American State Geologists (AASG), has supported compilation of a new national karst map and geographic information system (GIS) database since 2001. As part of this effort, the USGS sponsored several regional karst workshops with representative attendance by various interested state geological surveys and other karst scientists. A regional compilation map of karst in the states of the central and southern Appalachian region was published by Weary (2008).

The USGS has recently published a series of new national-scale maps depicting karst and potential karst areas of the United States as parts of an online Open-File Report titled *Karst in the*

*United States: A Digital Map Compilation and Database* (Weary and Doctor, 2014). The report contains a discussion and methodology text and five maps of karst and pseudokarst areas of the United States, including Puerto Rico and the U.S. Virgin Islands. The graphic files of these maps can be downloaded for display at scales of 1:6,000,000 for the contiguous United States and Alaska and 1:3,000,000 for Hawaii, Puerto Rico, and the U.S. Virgin Islands. These maps include a GIS database. The GIS data are available both as ESRI shapefiles or as files in compressed KML (.kmz) format. Opening these files into Google Earth™ allows display of the karst and pseudokarst polygons over aerial imagery and terrain models supported by Google Earth™. The data in this report are preliminary, and there is an expectation of upgrade in content, quality, and resolution in future versions.

## Discussion of Karst Mapping Concepts and Scope

Efforts to map karst distribution have normally taken a geology-based approach, effectively delineating areas with potential for karst development by compiling areas of soluble rocks from geologic maps (e.g., Williams and Ford, 2006). In this report, we have taken a similar geology-based approach by compiling regions of known and potential karst in the United States using the latest, most detailed digital geologic map information. While this approach is representative of karst potential, a complex interaction among many factors determines the formation, localization, and intensity of karst development. These include the bedrock geology (rock type and structure), tectonics, climate, sedimentary cover, vegetation, local hydrologic conditions, and time. However, even very sparse karst features evident at the land surface can indicate important groundwater flow processes that are characteristic of karst in the broader subsurface. Thus, we have included all areas containing soluble bedrock lithologies as potentially hosting karst features.

The new USGS national-scale karst map (Weary and Doctor, 2014) illustrates the extent and varieties of karst and potential karst across the United States, including areas of pseudokarst as suggested by Halliday (2007). Potential pseudokarst landscapes include areas underlain by geologic materials susceptible to formation of voids produced by lava flows, erosion of fine-grained sediments by piping (stoping), and melting of permafrost. Examples include lava tubes in relatively young (Miocene and younger) volcanic flow rocks (primarily basalts), sometimes referred to as vulcanokarst (U.S. Environmental Protection Agency, 2002), piping features within unconsolidated sediments in semiarid to arid regions (Parker, 1963; Jones, 1987), as well as areas of piping in sediments affected by intermittently or progressively thawing permafrost in Alaska. Pseudokarst landscapes in permafrost areas are also known as thermokarst (Sweeting, 1973). In addition, in some areas of the western United States, thick successions of layered volcanic rocks are known to have large integrated groundwater systems that resurge at large springs. Examples include the Columbia Plateau aquifer system in Oregon and Washington, and the Snake River Plain aquifer system in Idaho.

Several thematic maps are presented in the report (Weary and Doctor, 2014). They are: (1) karst and potential karst areas of relatively soluble rocks (e.g., limestone, dolomite, gypsum, anhydrite, halite, etc.) exposed at or buried to depths of less than 90 m (300 ft) below the ground surface in the contiguous United States; (2) karst and potential karst areas of relatively soluble rocks (e.g., limestone and dolomite) in Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands; (3) areas underlain by evaporite rocks at varying depths up to 2134 m (7000 ft); (4) areas with potential for pseudokarst features in the contiguous United States; and (5) areas with potential for pseudokarst features in Alaska and Hawaii. The maps in the report are intended to supersede the National Atlas map *Engineering Aspects of Karst* by Davies et al. (1984).

The extent of outcrop of soluble rocks provides a good first approximation of the distribution of karst and potential karst areas, particularly in parts of the United States with a humid climate. Criteria for further differentiation of the karst map units in this report include (1) climate of regions based on annual precipitation and ecoregion designation; (2) depth of burial and nature of the overlying sediments; and (3) degree of consolidation of the potentially karstic lithostratigraphic unit.

Ecoregions are areas having similar climate, physiography, geology, soils, and other natural features (U.S. Environmental Protection Agency, 2013). North America is divided into 182 level III ecoregions, the most detailed level currently available nationwide. These regions approximate the size and extent of many of the well-known karst regions in the United States. The extents of the level III ecoregions provide a spatial framework for classifying karst terrains into areas affected by similar climatic and physiographic conditions at regional scales.

## Data Sources

Most of the spatial data compiled in this project were derived from lithologic map unit polygons on geologic maps produced by the various state geological surveys. The original source maps are available for purchase or download from the respective state geological surveys. Much of the digital map data were compiled from a series of integrated geologic map databases for the United States produced by the USGS Mineral Resources Program, National Surveys and Analysis (NSA) Project (see http://mrdata.usgs.gov/geology/state/, accessed 14 January 2015). Use of the USGS digital geologic data provided a consistent data structure within which a derivative database of areas with potential for karst could be constructed. Edits, deletions, and additions to this database were made based on (1) comparison to other published karst maps (principally, Davies et al., 1984; Veni et al., 2001), (2) comments and contributions by other cave and karst researchers having local knowledge of particular areas, (3) the comprehensive compilation in Palmer and Palmer (2009), and (4) the personal knowledge of the authors. Further characterization of the karst areas was also accomplished via overlay analyses with other data, including distribution of glacially derived sediments

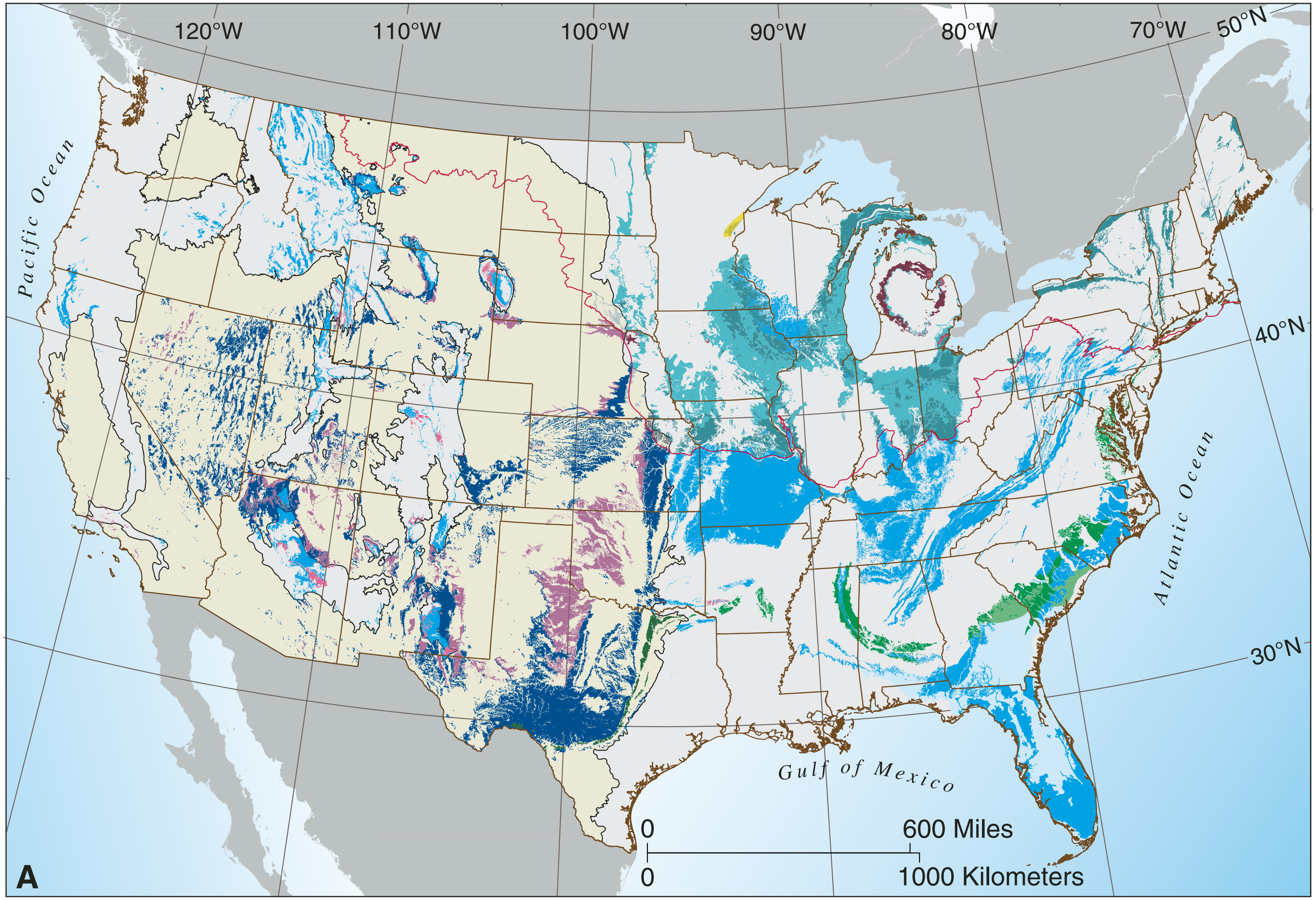


Figure 1 (*Continued on facing page*). (A) Map of karst and potential karst areas in the contiguous United States. Irregular red line indicates southern limit of late Cenozoic ice cover. See Weary and Doctor (2014) for a larger-scale representation of this map and the GIS data.

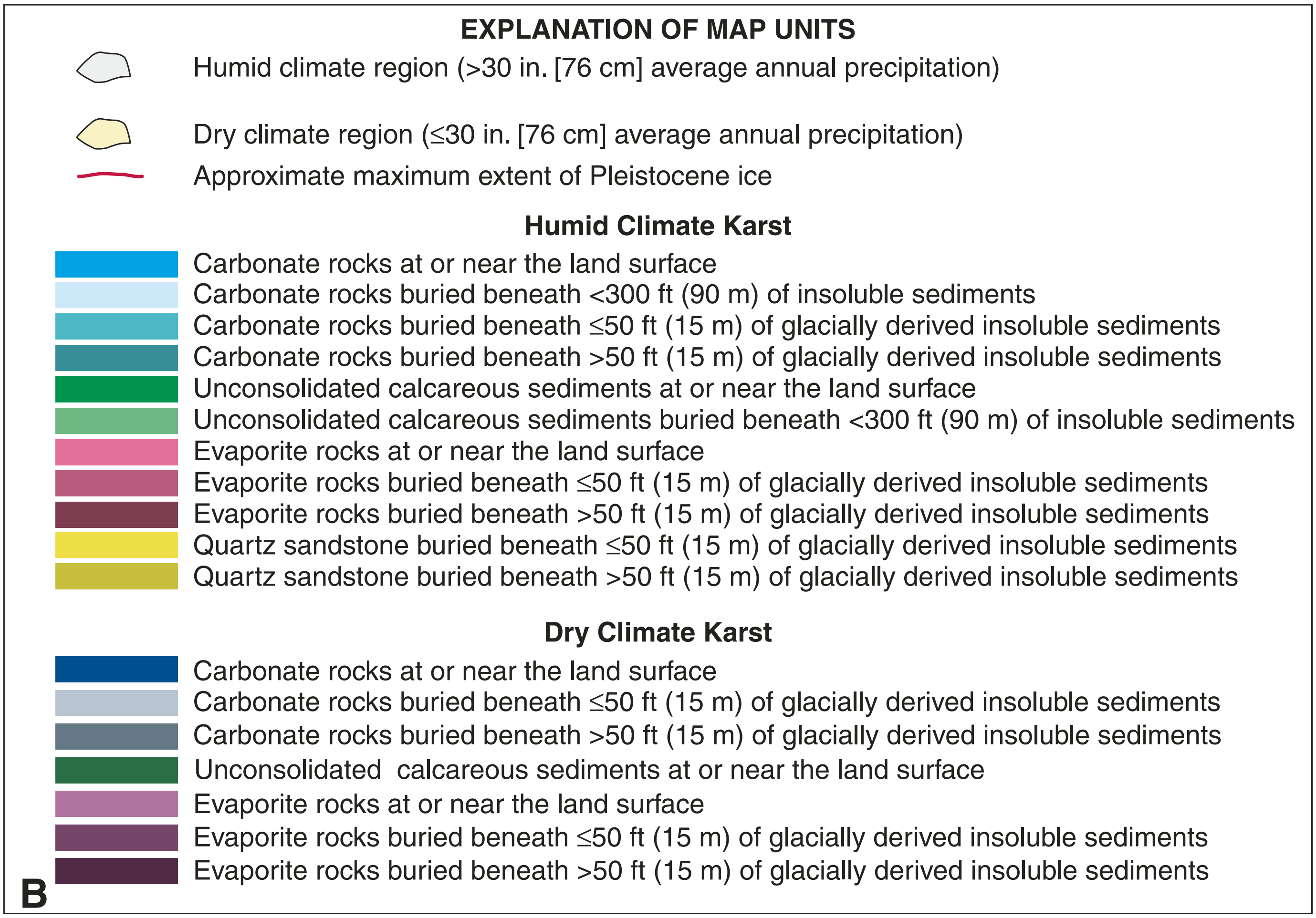


Figure 1 (*Continued*). (B) Explanation of maps symbols used on Figures 1A and 2.

(Soller et al., 2012), permanently frozen ground (Brown et al., 2002), and level III ecoregions (U.S. Environmental Protection Agency, 2013).

While it is beyond the scope of this paper to describe aspects of each individual karst region in detail, we refer the interested reader to the excellent volume *Caves and Karst of the USA* compiled by Palmer and Palmer (2009).

## KARST AND PSEUDOKARST AREAS IN THE UNITED STATES

The maps shown in Figures 1–5 were generated from GIS data of various resolution scales ranging from 1:24,000 to 1:500,000. The graphic files provided in Weary and Doctor (2014) are designed for display at 1:6,000,000 for the contiguous United States and Alaska, and 1:3,000,000 for Hawaii, Puerto Rico, and the U.S. Virgin Islands. The GIS data for all of these maps are in Albers projection using the North American horizontal datum of 1983.

### Karst in Soluble Rocks in the Contiguous United States

The distribution of karst and potential karst areas in soluble rocks in the contiguous United States is shown in Figure 1, and it is shown for Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands in Figure 2. Distribution of mature surface karst areas in the contiguous United States is primarily dependent on the presence of soluble rocks at or near the land surface and mean annual precipitation above ~30 in. (76 cm). In the more humid parts of the United States, most karst features such as caves and sinkholes (dolines) occur in carbonate (limestone and dolomite) rocks; evaporite rocks are rarely found at or near the surface in these areas. Most of the eastern United States and the Pacific coastal zone are humid. Locally, areas of the Rocky Mountains and the Sierra Nevada are also classified as humid regions, with greater effective precipitation mostly due to orogenic effects. All areas of Alaska, Hawaii, Puerto Rico, and the Virgin Islands are considered humid at the resolution of this study. In the semiarid and arid regions of the western United States, carbonates are more


Figure 2. Distribution of karst and potential karst areas in carbonate rocks in (A) Alaska, (B) Hawaii, and (C) Puerto Rico and the U.S. Virgin Islands. See Weary and Doctor (2014) for a larger-scale representation of this map and the GIS data.

resistant to erosion than in humid areas due to lower precipitation, and the most prominent karst features occur in the more soluble evaporite rocks that exist at or near the surface in those environments. Karst features created by hypogenic processes tend to be better preserved in arid and semiarid areas, as these features are less likely to be modified by epigenic processes in drier climates (Palmer, 2000; Auler and Smart, 2003).

The potentially karstic areas shown on Figure 1 are grouped by areas of humid climate and areas of dry (semiarid to arid) climate. In addition to carbonate and evaporite rocks, an area of quartz sandstone in Minnesota with documented solution karst is shown (Shade, 2002). Other areas of anomalous solution, in what are normally considered insoluble rocks, may exist elsewhere in the United States.

The boundaries between dry and humid regions on our maps (Figs. 1 and 3) were delineated by comparing the average annual precipitation map for the years 1961–1990 with descriptions of North American level III ecoregions (Daley and Taylor, 2000; U.S. Environmental Protection Agency, 2013). These boundaries are coincident with the level III ecoregion boundaries as they approximate the 30 in. (76 cm) per year annual average precipitation isohyet (Daley and Taylor, 2000). The humid regions are noted for moderate to strong chemical weathering, whereas the dry regions are areas of weak chemical weathering as determined by modeling of climate data and Peltier graphs (Fowler and Petersen, 2004; Peltier, 1950). These boundaries, although shown as solid lines on Figures 1 and 3, are actually diffuse and approximate. Because the boundaries were made to coincide with those of the ecoregions, karst in some marginal areas may be inaccurately portrayed at finer scales. In addition, some relatively dry areas of the United States are known to receive precipitation concentrated in particular seasons, resulting in erosionally effective precipitation and denudation rivaling or exceeding some areas classified as humid, even though they fail to exceed the average 30 in./yr (76 cm/yr) threshold. One example is Sequoia–Kings Canyon National Park, California, which receives less than 30 in. (76 cm) of precipitation per year, but receives most of its precipitation from January to mid-May.

The principal humid-dry boundary separating the eastern from the western areas of the United States also approximates the southern part of the 32.5 in. (82.5 cm) annual average precipitation isohyet discussed by Epstein and Johnson (2003). There is some divergence of the humid and dry region boundaries from the principal 30 in. (76 cm) precipitation line at both north and south latitudes, as the effective regional humidity is also a function of the regional evapotranspiration rate, which itself is affected by temperature. Occurrence of soluble rocks in either humid or dry regions is reflected in the map unit classifications on Figures 1, 2, and 3 and also in the database (Weary and Doctor, 2014).

Effects of late Cenozoic glaciations have a profound influence on the development and preservation of karst features, principally in the northern and eastern parts of the contiguous United States. The maximum extent of North American glaciations is shown on Figure 1. The thickness of glacially derived sediments overlying areas of soluble rocks, taken from Soller et al. (2012), is also integrated into the classification of map units. An area of exposed carbonate bedrock with no or thin glacially derived sediment cover exists where southeastern Minnesota, northeastern Iowa, southwestern Wisconsin, and northwestern Illinois converge. This region, the so-called "driftless area" (www.driftlessareainitiative.org/aboutus/defining_driftless.cfm, accessed 1 May 2014), has significantly greater karst feature development than the surrounding areas, which have thicker deposits of glacial sediments atop carbonate bedrock.

***Karst map units.*** Our map of karst areas in soluble rocks in the United States portrays potentially karstic areas based on the existence of soluble rocks at, or relatively near, the land surface. These areas are then subdivided by class of exposure, thickness of overlying insoluble sedimentary units, and by degree of consolidation.

***Carbonate rocks at or near the land surface.*** These areas are underlain directly by carbonate bedrock, including unconsolidated calcareous sediments in the Atlantic and Gulf Coastal Plains, or by a veneer of sediments covering carbonate bedrock or sediments. In humid regions, these units are typically karstified and contain varying densities of sinkholes, caves, and other karst features. Surface karst features such as solutional karren, solutionally enlarged fractures or pits in outcrops, and bedrock pinnacles surrounded by regolith comprise an epikarst that may be well developed locally, with relief in excess of 30 ft (9 m) in some areas. In semiarid and arid regions, these rocks may exhibit very few large karst features, and sinkholes become rare; rather, small-scale features such as karren become the most common types. It can be argued that many of these arid carbonate areas are not karstic under present climatic conditions; however, a number of deep-seated solutional karst and (or) paleokarst features may be exposed as a result of tectonic uplift and erosion (Palmer and Palmer, 2011).

***Carbonate rocks buried beneath <300 ft (90 m) of insoluble sediments.*** These are areas where carbonate rocks occur in the relatively shallow subsurface, and voids are known to propagate up through the cover of overlying sediment. In this study, only areas in the humid southeastern United States, southern Atlantic and Gulf Coastal Plains, and the Florida peninsula are classified as such. Other areas of the country, such as the Ozark Plateau, also have similar mantled landscapes but are not differentiated as such in this report.

***Carbonate rocks buried beneath ≤50 ft (15 m) of glacially derived insoluble sediments.*** These are areas of carbonate rocks overlain by thin deposits of glacially derived sediments. Units were identified for this classification by overlaying data from the map of Soller et al. (2012) on a map of carbonate bedrock units. Cover-collapse sinkholes are common in some of these areas where karst is overlain by loess or other cohesive unconsolidated deposits.

***Carbonate rocks buried beneath >50 ft (15 m) of glacially derived insoluble sediments.*** These are areas in the northeastern conterminous United States where carbonate rocks lie beneath

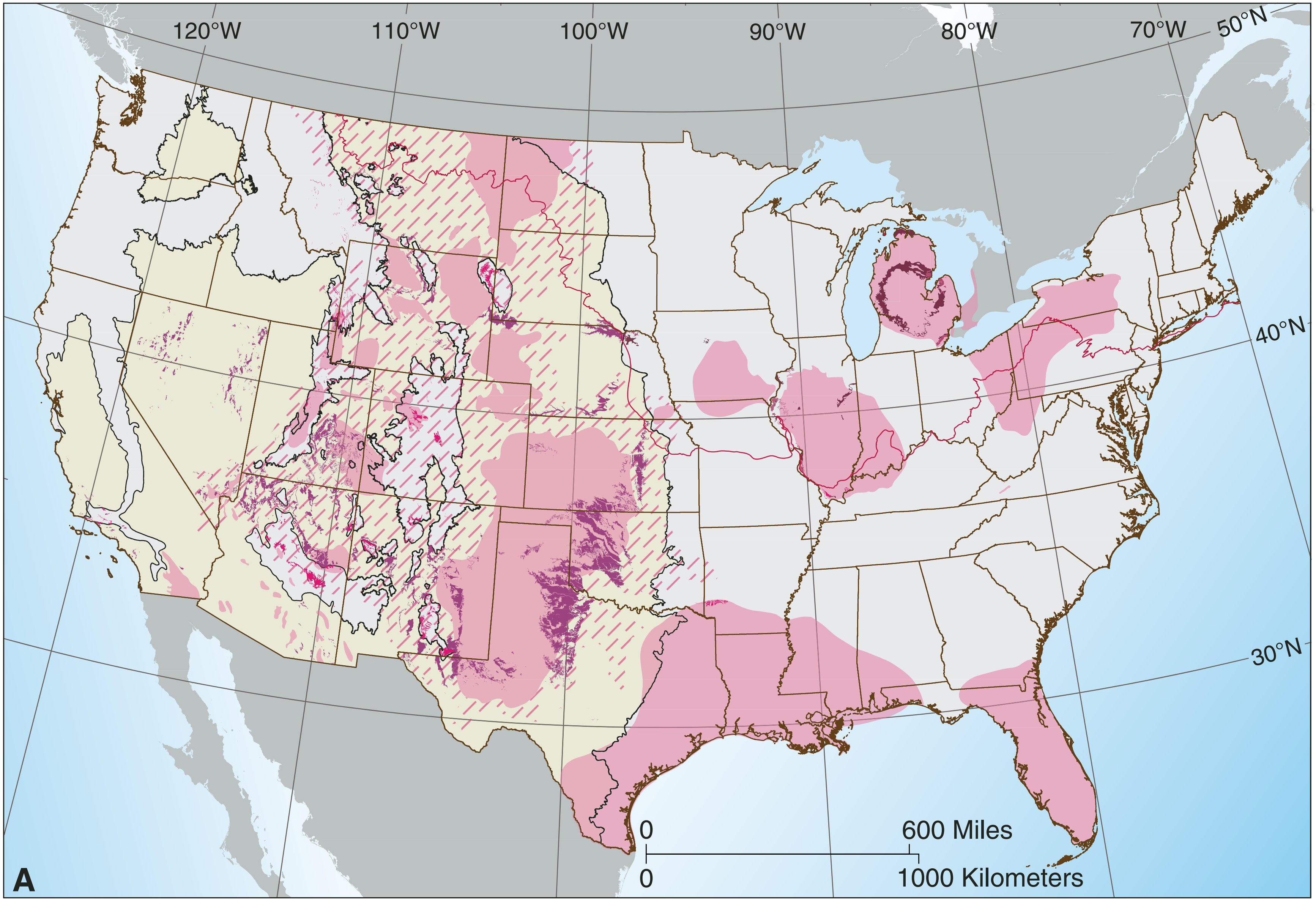


Figure 3 (*Continued on facing page*). (A) Areas underlain by evaporite rocks at various depths up to 7000 ft (2134 m) below the land surface. See Weary and Doctor (2014) for access to a larger-scale representation of this map and the GIS data.

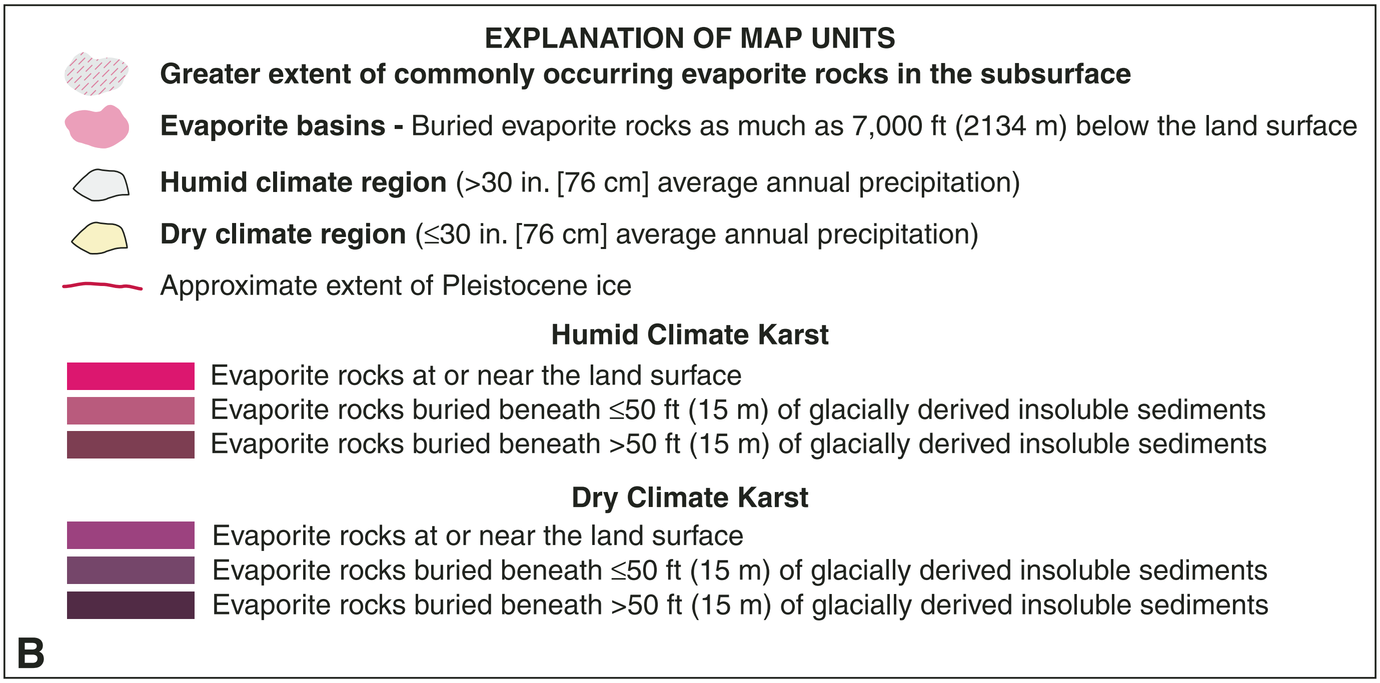


Figure 3 (*Continued*). (B) Explanation of map symbols used.

relatively thick deposits of glacially derived sediments such as drift. The vast majority of these areas occur in the humid region of the eastern United States. Because of the overlying sedimentary cover, karst features are rare at the surface. However, these buried carbonate rocks may be vulnerable to groundwater contamination, particularly in areas where they are covered by high-permeability sediments.

***Unconsolidated calcareous or carbonate rocks at or near the land surface.*** These are areas underlain by poorly consolidated sedimentary rocks at or generally within 100 ft (30 m) of the surface. These are chiefly Mesozoic and Cenozoic marine sediments along the Atlantic and Gulf Coastal Plains. Rock types range from chalks to marls and other units rich in calcareous fossil shell material. These units are generally not prone to cave or subterranean void formation; however, local high-permeability zones with conduits may develop along contacts with less soluble units such as shales and sandstones. The most common karst feature in these units are subtle shallow depressions (sinkholes) produced by localized dissolution of the carbonate material.

***Unconsolidated calcareous or carbonate rocks buried beneath <300 ft (90 m) of insoluble sediments.*** These are areas of calcareous sediment or poorly consolidated carbonate rocks buried by as much as 300 ft (90 m) of insoluble sediments. Ground subsidence and sinkholes rarely occur in these areas.

***Evaporite rocks exposed at or near the land surface.*** These are areas of evaporite rocks, principally gypsum, anhydrite, and halite, exposed at or near the surface. Most outcrops occur in the western parts of the contiguous United States in semiarid to arid climates. Areas of this unit in the Great Lakes region and Illinois comprise Paleozoic strata with interbedded evaporite mineral deposits. Solution cavities, caves, and sinkholes are the primary karst-related hazards in the semiarid and arid regions.

***Evaporite rocks buried beneath ≤50 ft (15 m) of glacially derived insoluble sediments.*** These are evaporite rocks buried beneath ≤50 ft (15 m) of glacially derived sediments. Most of these occurrences are in the Michigan Basin.

***Evaporite rocks buried beneath >50 ft (15 m) of glacially derived insoluble sediments.*** These are areas of evaporite rocks buried beneath >50 ft (15 m) of glacially derived sediments. Most of these occurrences are in the Great Lakes and Midwestern regions.

***Quartz sandstone buried beneath ≤50 ft (15 m) of glacially derived insoluble sediments.*** Karst features including sinkholes, stream sinks, springs, and short caves have been documented in an area of quartz sandstone (Hinckley Sandstone) in Pine County, east-central Minnesota (Shade, 2002). Most of this area is mantled with deposits of glacially derived sediments of various thickness.

***Quartz sandstone buried beneath >50 ft (15 m) of glacially derived insoluble sediments.*** Some areas of quartz sandstone (Hinckley Sandstone) are buried beneath relatively thick deposits of glacially derived insoluble sediments. Surface expression of karst features is less likely in these areas.

**Karst in Soluble Rocks in Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands**

The spatial distribution of potentially karstic carbonate rocks occurring at or near the surface in Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands is shown as a single map unit on

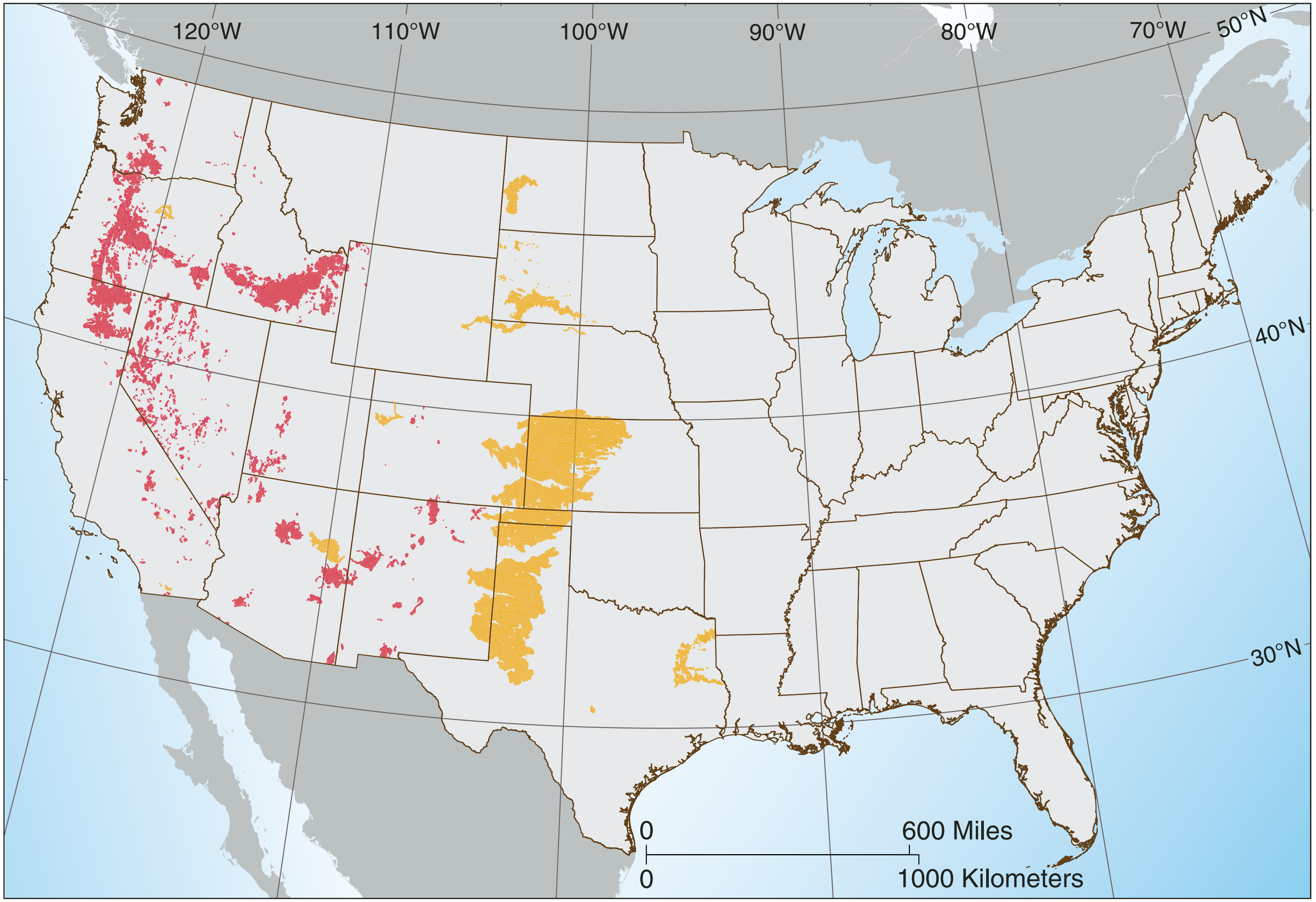


Figure 4. Areas of known pseudokarst features in the contiguous United States. Areas with potential for lava tubes are shown in red, and areas with potential for piping features are shown in orange. See Weary and Doctor (2014) for a larger-scale representation of this map and the GIS data.

Figure 2. All of these areas have relatively humid climates, so evaporite rocks generally do not occur at or near the surface.

Carbonate areas found in the temperate rain forests of southeastern Alaska comprise the best-developed and most well-known karst in that state. Little is known about other karst areas to the north and west, but carbonate rocks are abundant.

Karst in Hawaii occurs in relatively young, island-fringing limestones. Small areas of these limestones occur on all of the major islands of Hawaii with the exceptions of Kaho'olawe and Hawai'i.

The U.S. Commonwealth of Puerto Rico has areas of well-developed karst in both Mesozoic and Cenozoic limestones. Most of the larger karst features occur in the northwestern and north-central parts of the island, where very large and abundant sinkholes occur. The large Puerto Rican Island of Mona (Isla de la Mona) to the west of the main island is almost 100% karst.

The U.S. Virgin Islands contain areas of Cenozoic limestone and dolomite bearing karst features. These areas occur in the central part of the island of St. Croix and along the northern parts of the islands of St. Thomas and St. John.

## Areas Underlain by Evaporite Rocks at Various Depths up to 7000 ft (2134 m) below the Land Surface in the Contiguous United States

In addition to showing areas of outcropping and near-surface evaporite rocks in the contiguous United States, Figure 3 shows the extent of subsurface evaporite basins and the greater extent of commonly occurring evaporite rocks in the subsurface. The evaporite basins contain soluble rocks buried to depths of as much as 7000 ft (2134 m), but generally much less. This maximum depth is based on depths of solution mining reported by Dunrud and Nevins (1981). Because of the physical properties and very high solubility of evaporite rocks, human activities such as fluid injection, or the occurrence of leakage from well casings, can induce the formation of large solution voids. Collapses of these voids are known to propagate up to the surface from depths of more than 1000 ft (305 m). The area of greater extent of subsurface evaporite rocks contains mainly gypsum and anhydrite interbedded with nonevaporite rocks (modified from Johnson, 2008). The extent of the evaporite basins is derived in part from information in Dunrud and Nevins (1981) and Johnson (2008).

## Areas Having Potential for Development of Pseudokarst Features in the Contiguous United States

Two different units are portrayed on the map of pseudokarst areas of the contiguous United States (Fig. 4). These are: (1) areas of poorly consolidated sedimentary rock units known, at least locally, to contain piping features (tubes, caves, and subsidence features), and (2) areas of volcanic rock that contain or may contain lava tubes and/or layered volcanic rocks with integrated fast-groundwater-flow systems. Lava tube terrains are sometimes termed vulcanokarst (U.S. Environmental Protection Agency, 2002). Lava tubes form most readily in low-viscosity lava flows, usually of basaltic composition. Lava tube caves are relatively short-lived geologic features, as they are either filled by succeeding eruptive lavas, or because, as near-surface features, they are susceptible to erosion and collapse of overlying rocks. Lava tubes are generally not found in rocks older than Miocene age, and this age was used as a cutoff for selecting volcanic flow units for this map.

Most of the areas of piping potential occur in fine-grained sedimentary rocks in the High Plains region, the Badlands regions of North and South Dakota, western Colorado, east Texas, northeast Arizona, and southern California (Parker, 1963). The areas portrayed are those that contain known pseudokarst features; however, areas with potential for such features are more widespread.

## Areas Having Potential for Development of Volcanic or Thermokarst Pseudokarst Features in Alaska and Hawaii

Because of their relatively recent and ongoing volcanism, both Alaska and Hawaii contain abundant relatively young (<Miocene age or younger) lava flow deposits that contain lava tubes and other pseudokarst features. These volcanic pseudokarst areas are shown as a single map unit (Figs. 5A and 5B).

The cold climate of Alaska results in extensive regions of permafrost, or frozen ground (Fig. 5A; Brown et al., 2002). As temperatures rise, these areas experience melting, resulting in landforms and hydrologic conditions, such as sinkholes and sinking streams, that are analogous to karst terrains. Because this phenomenon is related to melting of ice rather than solution of bedrock, these permafrost features are considered a category of pseudokarst (Halliday, 2007) and are termed thermokarst (Sweeting, 1973, p. 308).

### *Thermokarst Map Units*

These are areas in Alaska with potential for thermokarst features classified on the basis of continuity of permafrost, ice content, and overburden thickness (Fig. 5). Ice content is defined as the relative abundance of ground ice in the upper 20 m and is estimated in percent volume. Three classes of ground ice content were identified: high (>20%), medium (10%–20%), and, low (<10%; Brown et al., 2002). Overburden was considered to be thick everywhere surficial units were depicted on the geologic map of Reed and Bush (2005).

## Spatial Statistics

Simple spatial statistics were calculated from the area of the United States, in percent, underlain by the areas of karst and pseudokarst defined in this report. Because the other U.S. territories were not included in this report, statistics for karst areas of Puerto Rico and the U.S. Virgin Islands were not included in these calculations. The results are presented in Figure 6. In summary, ~25% of the United States is underlain by rocks and


Figure 5. Areas with potential for development of lava-tube or thermokarst pseudokarst features in (A) Alaska and (B) Hawaii. See Weary and Doctor (2014) for access to a larger-scale representation of this map and the GIS data.

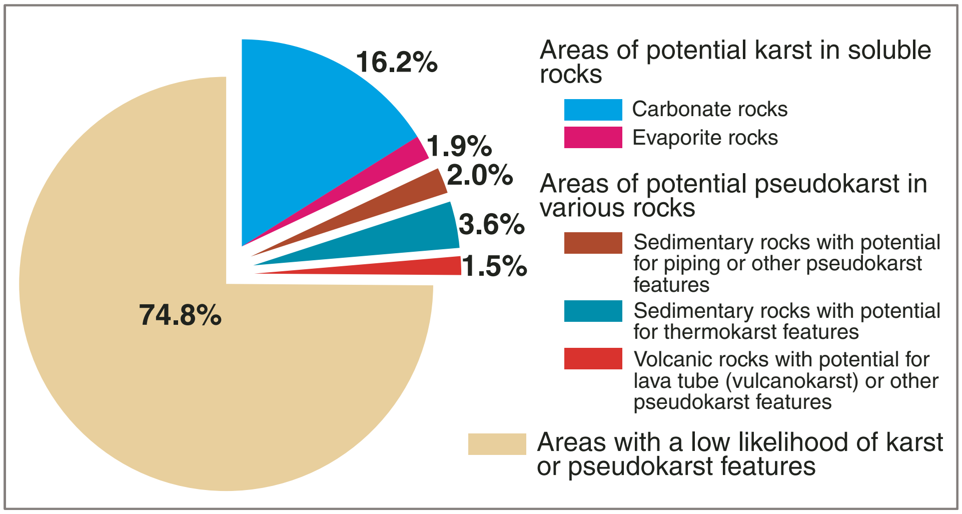


Figure 6. Proportion of the area of the 50 United States underlain by potentially karstic and pseudokarstic rocks.

sediments of all types having karst or pseudokarst features or a potential for them. About 18% of the country is underlain by soluble rocks, excluding the areas of quartz sandstone in Minnesota. Within this category, 16% of the nation is composed of carbonate rocks, and 2% is evaporite rocks. The area of the country underlain by basins where evaporite rocks may be encountered by deep drilling (up to 7000 ft [2134 m]) was not included in the calculations for Figure 6 because, technically, these rocks at depth are not karst. Moreover, these values underestimate the area of the United States underlain by karst aquifers, a major source of potable water for the nation. About 2% of the United States is underlain by sedimentary rocks prone to development of pseudokarst features, primarily by piping. Approximately 3.6% of the country, restricted to Alaska, is underlain by permafrost areas having potential for thermokarst. Lastly, ~1.5% of the total area of the United States, which includes western parts of the contiguous United States, Alaska, and Hawaii, are underlain by volcanic rocks having potential for lava tubes.

## SUMMARY AND CONCLUSIONS

About 18% of the area of the United States is underlain by soluble rocks with potential for development of karst features. These areas are further classified into karst map units on the basis of general climate setting, degree of induration, and exposure. About 7.1% of the area of the United States is underlain by sedimentary or volcanic rocks with potential for pseudokarst features. These karst and pseudokarst areas are graphically portrayed in the figures included with this report, and they are also represented in a GIS database as polygon features.

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