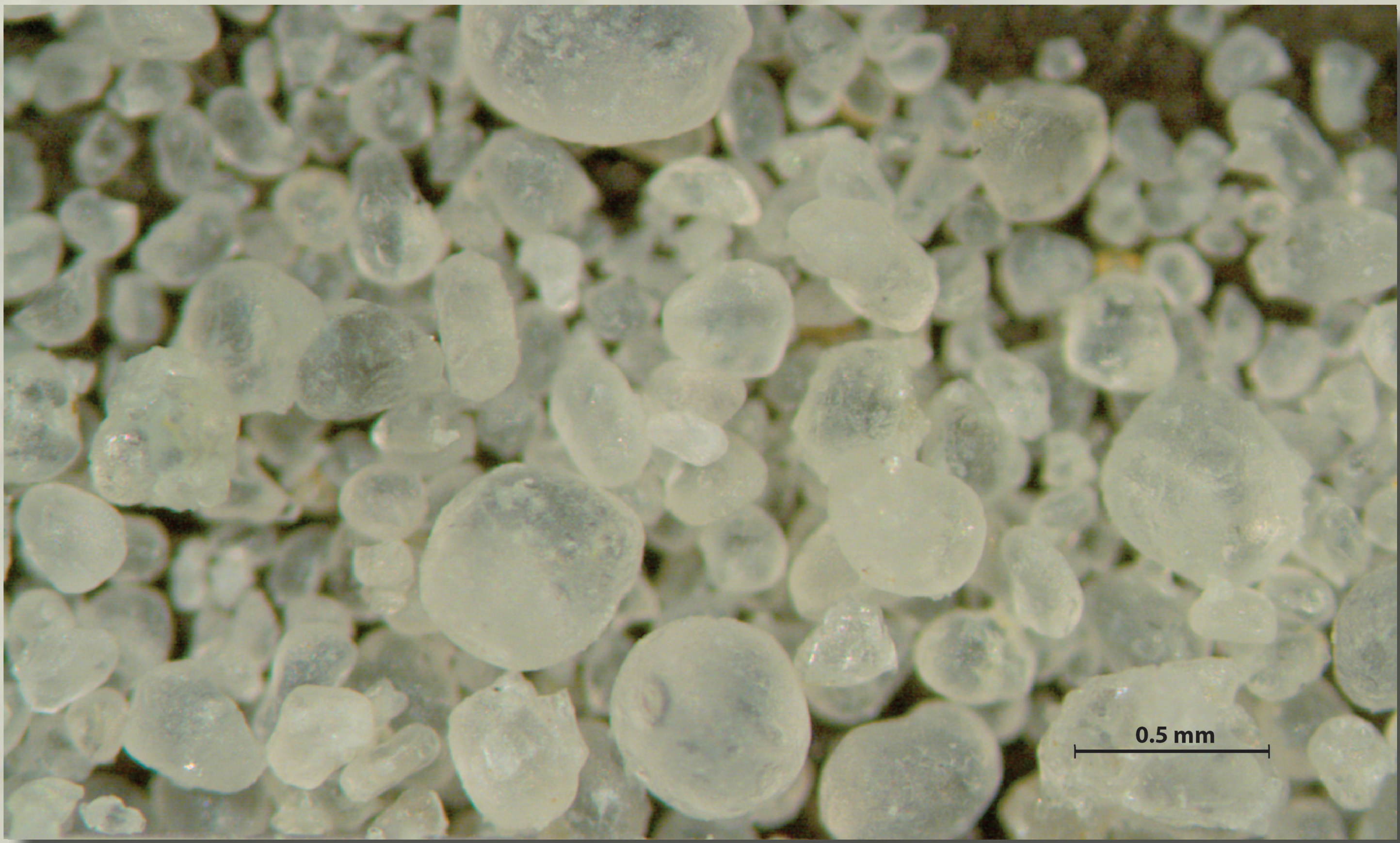
Frac Sand in the United States—A Geological and Industry Overview



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U.S. Department of the Interior
U.S. Geological Survey

Frac Sand in the United States—A Geological and Industry Overview

By Mary Ellen Benson and Anna B. Wilson

With a section on Frac Sand Consumption History contributed by Donald I. Bleiwas

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Cover photograph: Unsorted sample of St. Peter Sandstone, a major source for frac sand in the Midwest. By Mary Ellen Benson, USGS.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
	Density	
grams per cubic centimeter (g/cm^3)	1,000.0	kilograms per cubic centimeter (kg/m^3)
pounds per cubic foot (lb/ft^3)	0.01601846	grams per cubic centimeter (g/cm^3)
	Weight	
short ton	2,000	pounds (lbs)
metric ton (tonne or m.t.)	2,205	pounds (lbs)

Abbreviations Used in This Report

API American Petroleum Institute

cm centimeter

FOB "free on board": Commonly used when shipping goods to indicate who pays loading and transportation costs, and (or) the point at which the responsibility of the goods transfers from shipper to buyer.

ft feet

FTU formazin turbidity units

g/cm^3 grams per cubic centimeter

GIS geographic information system

in. inch

ISO International Organization for Standards

km kilometer

lb/ft^3 pounds per cubic foot

m meter

mg/L milligram per liter

mi mile

mm millimeter

MRDS Minerals Resource Data System

mtpa million metric tons per annum

NTU nephelometric turbidity units

psi pounds per square inch

SGMC U.S. Geological Survey State Geology Map Compilation

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Abstract

A new mineral rush is underway in the upper Midwest of the United States, especially in Wisconsin and Minnesota, for deposits of high-quality frac sand that the mining industry calls "Northern White" sand or "Ottawa" sand. Frac sand is a specialized type of sand that is added to fracking fluids that are injected into unconventional oil and gas wells during hydraulic fracturing (fracking or hydrofracking), a process that enhances petroleum extraction from tight (low permeability) reservoirs. Frac sand consists of natural sand grains with strict mineralogical and textural specifications that act as a proppant (keeping induced fractures open), extending the time of release and the flow rate of hydrocarbons from fractured rock surfaces in contact with the wellbore.

The current sand mining surge has been driven by the boom in unconventional oil and gas production that has been largely spurred by advancements in technology promoting the expansion of hydraulic fracturing and horizontal drilling over the past decade. Because of its superior quality, the sand of the upper Midwest not only supports the majority of domestic oil and gas production, but it also supplies frac sand to some of Canada's western shale basins.

The principal sources of "Northern White" or "Ottawa" sand in the upper Midwest are the Middle and Upper Ordovician St. Peter Sandstone and the Lower Ordovician and Upper Cambrian Jordan Formation, with the Upper Cambrian Wonewoc and Mount Simon Formations gaining in importance. Additional frac sand sources to the south include the Upper Cambrian Hickory Sandstone Member of the Riley Formation in Texas, which is referred to informally as "Brown" or "Brady" sand, and the Middle Ordovician Oil Creek Formation in Oklahoma.

More than 40 United States industry operators are involved in the mining, processing, transportation, and distribution of frac sand to a robust market that is fast-growing in the United States and throughout the world. In addition to the abrupt rise in frac sand mining and distribution, a new industry has emerged from the production of alternative proppants, such as coated sand and synthetic beads. Alternative proppants, developed through new technologies, are competing with supplies of natural frac sand. In the long term, the vitality of both industries will be tied to the future of hydraulic fracturing of tight oil and gas reservoirs, which will be driven by the anticipated increases in global energy consumption.

Introduction—Overview of Frac Sand as a Commodity

There is a growing demand from the public, government agencies, and the energy and mineral resource industries for credible information about frac sand and the frac sand resource industry. More than 40 United States (U.S.) companies are involved in mining, transporting, processing, and distributing frac sands to a robust market that is fast-growing in the United States and throughout the world. The need to reduce costs and ensure continued and consistent supplies of frac sand has resulted in the acquisition of frac sand mines by several petroleum producers and in collaborative agreements between several frac sand suppliers and rail lines.

Frac sand, as a commodity, is a naturally occurring, highly pure silica sand, with rigorous physical specifications, that is used as a proppant during hydraulic fracturing (fracking or hydrofracking) of oil and gas wells to maximize production from tight, unconventional reservoirs (Beckwith, 2011). In the United States, it is mined primarily from Cambrian and Ordovician sandstone units in the upper Midwest and the south-central region. Tight gas and oil reservoirs are low-permeability sandstones, shales, and carbonates, or coalbed methane reservoirs that cannot be produced at economic flow rates or that cannot recover economic volumes of gas unless the well is stimulated by a large hydraulic fracture treatment and (or) produced using horizontal wellbores (Oil and Gas Journal, 2014). Although hydraulic fracturing is used in multiple types of tight reservoirs, the process is more effective in methane and natural gas reservoirs because the molecules of methane and natural gas are smaller than those of crude oil, so they tend to be more responsive to fracking (Ratner and Tiemann, 2014). The current hydraulic fracture treatment process involves multi-stage fracturing of as many as a few dozen stages, allowing for a large number of fractures to be created at specific locations within a single wellbore (Rock Products, 2014c). A proppant is a granular material that is added to the fracking fluid to prop open the fractured formation to promote the flow of hydrocarbons during the well's productive life (Beckwith, 2011). Because proppants can be customized for the particular reservoir, well, or treatment design, highly specialized proppants produce increasingly optimal results.

The physical properties of frac sand, as defined by the American Petroleum Institute (API), are quite specific. The optimal frac sand is a naturally occurring, unconsolidated silica sand or friable sandstone that has a nearly pure quartz composition, crush-resistant grains, high sphericity/roundness of grains, and a uniformly medium- to coarse-grain size. Additional factors that influence the economics of mining are the deposit's areal extent and thickness, textural uniformity, accessibility at or near the surface, nearness to trucking and rail transportation routes, and proximity to the active unconventional petroleum basins.

In addition to naturally occurring frac sand (also referred to as "raw frac sand"), alternative proppants are a significant part of the proppant market. These include resin-coated sand and synthetic proppants engineered from high-strength ceramic materials such as sintered bauxite (Dolley, 2012). Although the supply of natural frac sand, supplemented by alternative proppants, has been sufficient to meet the current demand, future depletion of sand sources is expected to drive higher costs along with increased concerns about environmental impacts of mining and handling of frac sand. The higher performance of synthetic proppants under higher pressure conditions in reservoirs at greater depth has made the higher cost of the ceramic materials cost-effective in some shale basins (ShanXi GuangYu Ceramic Proppants, 2012). Due to these and other economic factors, the future of the fracking industry may increasingly require greater dependence upon alternative, manufactured proppants.

The goals of this report are to provide basic information about frac sand as a resource, identify its unique physical properties, give an overview of processes of origin for frac sand deposits, describe and show the distribution of the geologic units that are currently yielding high-and medium-quality frac sand and seed sand best suited for resin coating, recognize for future examination some of the additional sand sources that have limited suitability, identify primary areas of frac sand industry activity, highlight key considerations in the development of frac sand as a resource, and summarize the general trends in the frac sand/proppants market. The map figures, plate, and geographic information system (GIS) data graphically illustrate the geographic distribution of major current and potential frac sand sources within the conterminous United States. The GIS dataset was developed from digital data from the U.S. Geological Survey State Geology Map Compilation project (SGMC), in preparation (J.D. Horton, C.A. San Juan, and D.B. Stoeser, unpub. data).

Stratigraphic nomenclature conforms to that provided by the references, as cited, except where names of units are modified to conform to U.S. Geological Survey conventions. Stratigraphic units are discussed in the order of geologic age (oldest to youngest), except where otherwise noted. Listings of States are in geographic order of regions, as indicated. Canadian Provinces and companies are discussed in alphabetical order. Note that whenever units of measurement are provided in this report, the first value given is in units as published in the referenced citation, and where converted to other units, these values are shown subsequently in parentheses.

Physical Properties of Premium Quality Frac Sand

The specifications for frac sand are based upon the standards for proppants determined by the American Petroleum Institute (API) and the International Organization for Standards (ISO). The current API/ISO Standards for frac sand (proppants) are defined in the API RP 19C/ISO 13503-2, "Recommended Practice for Measurement of Properties of Proppants Used in Hydraulic Fracturing and Gravel-packing Operations," which replaces RP 56 and RP 58 (American Petroleum Institute and others, 2008). API RP 19C/ISO 13503-2:2006 dictates the standard testing procedures used to evaluate and compare certain physical properties of proppants used in the above practices.

These frac sand standards were modeled after the properties of the "Ottawa" sand or "Northern White" sand and the "Brady Brown" sand (Zdunczyk, 2014). The Ottawa sand, a synonym for the St. Peter Sandstone mined from Ottawa, Illinois (Maslowski, 2012), is used as a standard by the American Society of Testing Materials (ASTM) (Zdunczyk, 2014). The frac sand specifications include criteria for mineralogy (high percent silica content), grain size range from medium to coarse, sphericity and roundness of 0.6 or greater, high crush resistance, low solubility, low turbidity, and good friability (American Petroleum Institute and others, 2008). These properties are detailed in the following paragraphs. A sample of premium quality frac sand with a high silica content, homogeneous grain size, and well-rounded and spherical grains is shown in figure 1.

To determine the type and quality of frac sand in a deposit, representative samples must be tested. A comparison of a sample of 40/70 Ottawa sand with the ISO 13503-2 specifications for frac sand is shown (U.S. Silica, 2014e) (fig. 2).

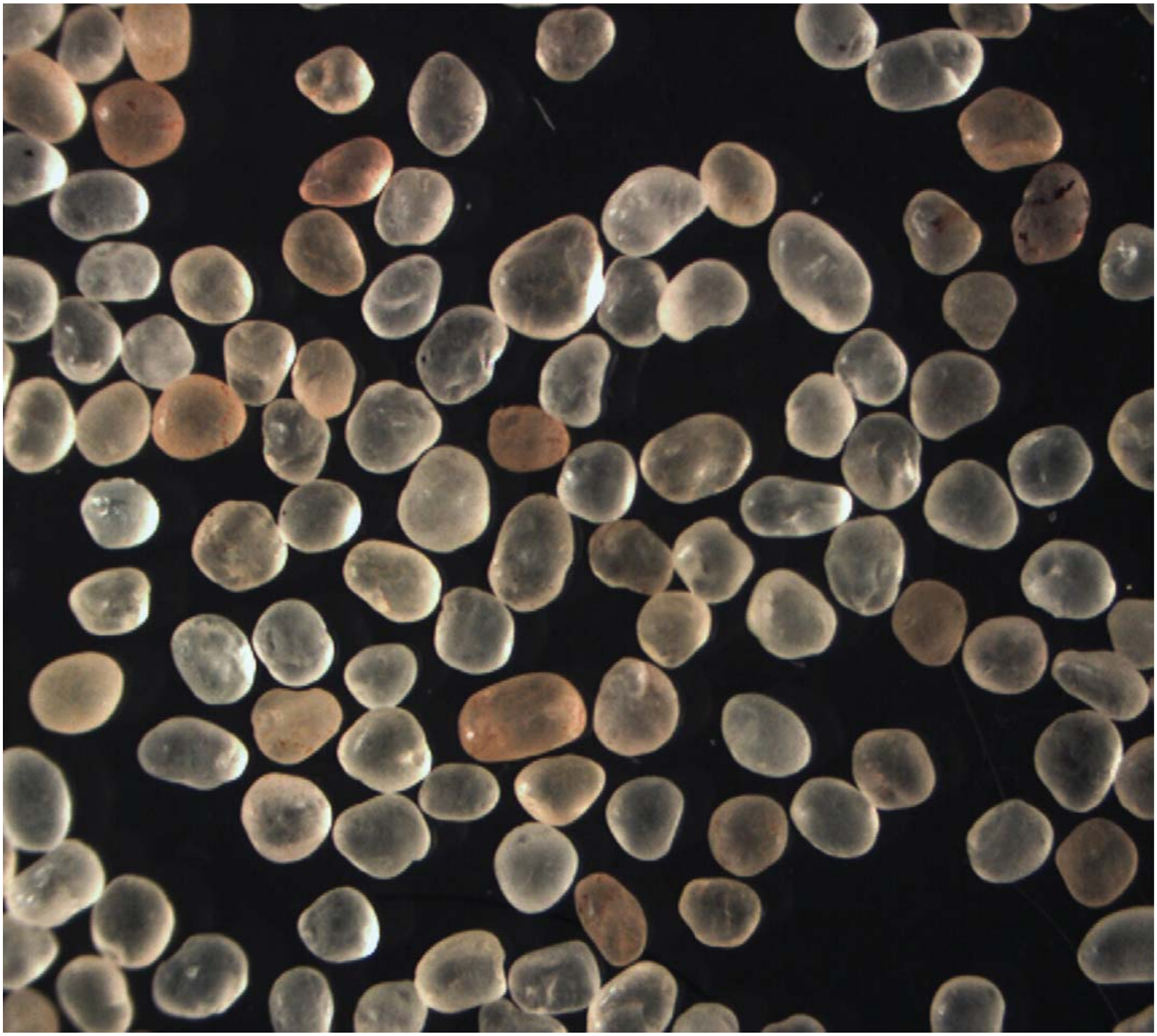


Figure 1. A magnified sample of “Northern White” frac sand. (Photo courtesy of Fairmount Santrol, 2014).

Typical properties			ISO 103503-2	40/70 Ottawa
Turbidity (NTU)			≤250	26
Krumbein shape factors				
Roundness			≥0.6	0.7
Sphericity			≥0.6	0.7
Clusters (%)			≤1.0	0
Bulk density (g/cm^3)				1.46
Bulk density (lb/ft^3)				91
Specific gravity				2.65
Mean particle diameter, mm				0.298
Median particle diameter (MPD), mm				0.29
Solubility in 12/3 HCl/HF for 0.5 hr @ 150ºF (weight loss %)			≤3.0	1.4
Particle size distribution	**mm**	**U.S. sieve no.**	**wt. % retained**	**wt. % retained**
	0.600	30	≤.01	0
	0.425	40		1.3
	0.355	45		13.7
	0.300	50		32.3
	0.250	60		26.3
	0.212	70		23.4
	0.150	100		2.9
	<0.150	Pan	≤1.0	0
	Total			100
	40/70 size		≥90	95.7
Crush resistance			**wt. % fines generated**	**wt. % fines generated**
@8,000 psi			≤10	9.6
@9,000 psi			≤10	13.3
K-value				8k

Figure 2. Typical properties of frac sand showing a comparison of 40/70 Ottawa sand properties with ISO 13503-2 frac sand standards (modified from U.S. Silica, 2014e). NTU, nephelometric turbidity units; ≤, less than or equal to; ≥, greater than or equal to; %, percent; g/cm^3, grams per cubic centimeter; lb/ft^3, pounds per cubic foot; mm, millimeter; HCL, hydrochloric; HF, hydrofluoric; °F, degree Fahrenheit; psi, pounds per square inch; wt., weight; k-value, maximum crush resistance in thousands psi.

High Silica Content

Premium frac sand is greater than (>) 99 percent quartz or silica (SiO_2) (Zdunczyk, 2007, 2014), although a great deal of sand used as frac sand falls within the range of 95–99 percent silica content. Mineralogical purity of silica content is a characteristic of mature and super-mature sand or sandstone, which has been highly reworked and well sorted, so that mechanically and chemically less-resistant minerals and fine particles have been dissolved or winnowed away (Pettijohn and others, 1972).

Homogeneous Grain Size

Generally, a range of grain sizes from 0.1- to >2-millimeters (mm) diameter is desirable. In “U.S. Standard Sieve Series sizes” or “U.S. Mesh,” this size range is equivalent to sieve opening sizes from 100 to >2,000 micrometers (µm) (fig. 3). In this system, the smaller the grain-size number, the coarser the grain (Beckwith, 2011). Grain-size ranges for sand samples are designated by notations such as 20/40, 30/50, 40/70, and so forth, that indicate the end-member mesh sizes for >90 percent of the sample. In the case of 20/40 sand, >90 percent of the sand passes through the 20-mesh (0.850-mm or 850-micron) sieve and is retained by the 40-mesh (0.425-mm or 425-micron) sieve (Zdunczyk, 2014) (fig. 3).

Proppant size designation										
Sieve-opening sizes (µm)[a]										
	3,350/1,700	2,360/1,180	1,700/1,000	1,700/850	1,180/850	1,180/600	850/425	600/300	425/250	212/106
Typical proppant/gravel-pack size designations										
	6/12	8/16	12/18	12/20	16/20	16/30	20/40	30/50	40/70	70/140
Stack of ASTM sieves[b]										
First primary sieve in bold type	4	6	8	8	12	12	16	20	30	50
	6	**8**	**12**	**12**	**16**	**16**	**20**	**30**	**40**	**70**
	8	10	14	14	18	18	25	35	45	80
Second primary sieve in bold type	10	12	16	16	**20**	20	30	40	50	100
	12	14	**18**	18	25	25	35	45	60	120
	14	**16**	20	**20**	30	**30**	**40**	**50**	**70**	**140**
	16	20	30	30	40	40	50	70	100	200
	pan	pan	pan	pan	pan	pan	pan	pan	pan	pan

[a]Sieve series as defined in ASTM E11

[b]Sieves stacked in order from top to bottom

Figure 3. Chart showing proppant size designations. The example of 20/40 sand is outlined in red and highlighted in yellow (modified from Getty, 2013). µm, micrometer.

Larger sand grains provide better permeability, but smaller sand grains are typically stronger (Rupke, 2014). Grain-size requirements for frac sand are determined by downhole conditions and completion design, but 20/40 mesh size has been the most in demand (Beckwith, 2011; Montgomery and Smith, 2010). Typically, 20/40 and 30/50 are most popular for oil fracking, and 40/70 and 70/140 are most commonly used for gas fracking (Zdunczyk, 2014). The use of 40/70 and the finer 100 mesh sands has increased in response to growth in gas development in the Barnett, Fayetteville, Haynesville, and Marcellus shale plays (Beckwith, 2011). Although the 100 mesh and finer mesh (70/140) typically have poor performance in proppant laboratory tests, their increased use in shale gas well fracturing is due to their capacity to block downward growth of fractures and to wedge open natural fractures (Zdunczyk, 2014).

High Sphericity and Roundness

Shape factors are based upon the Krumbein and Sloss chart for visual estimation of sphericity and roundness (Krumbein and Sloss, 1963), with the ISO 13503-2/API RP19C standards for frac sand at ≥0.6 for each (American Petroleum Institute and others, 2008) (fig. 4).

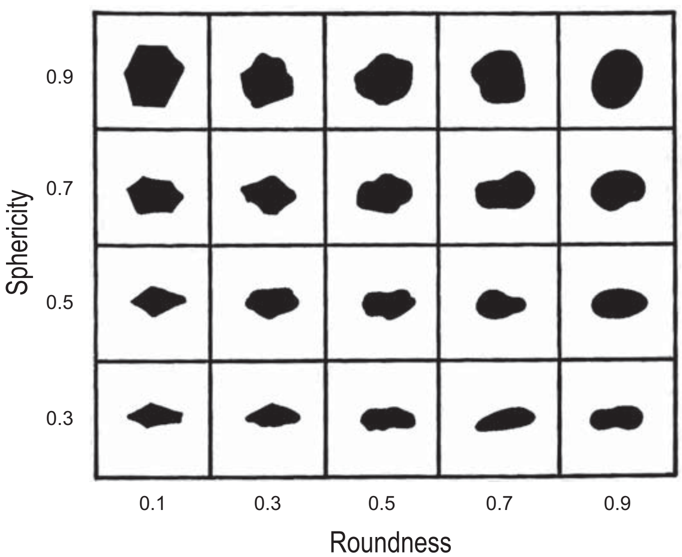


Figure 4. Proppant shape chart based on sphericity and roundness of Krumbein and Sloss (1963).

The greater roundness/sphericity provides better porosity/permeability between grains, allowing better flow of oil and gas from the fractures to the wellhead (Zdunczyk, 2014). The spherical shape also enables the grains to be carried in the fracking fluid with minimal turbulence (Geology, 2013).

High Crush Resistance

The selection of frac sand used in a hydraulic fracturing job is made with consideration of the crush resistance of individual sand grains necessary to keep the fractures open at different depths and temperatures in the target reservoirs. The bottom-hole pressures in some of the most productive U.S. shale gas plays (the Fayetteville, Barnett, Eagle Ford, and Haynesville) range from 2,000 to 10,000 pounds per square inch (psi), respectively (McCurdy, 2011).

The API crush resistance standard for proppants is measured in weight percent of fines generated under specific loading pressures to as much as 9,000 psi, and it varies for each grain-size range (mesh sizes) (American Petroleum Institute and others, 2008). For example, at 4,000 psi, the 6/12 mesh should yield ≤20 weight percent fines; 16/30 mesh and 20/40 mesh should yield ≤14 weight percent fines; 30/50 mesh should yield ≤10 weight percent fines; and 40/70 mesh should yield ≤6 weight percent fines (Zdunczyk, 2007). The pressure test results are expressed as a k-value that indicates the highest number of psi pressure × 1,000 that generates ≤10 weight percent fines (American Petroleum Institute and others, 2008). For example, a k-value of 8 means that, at 8,000 psi pressure, no more than 10 weight percent fines were generated, but more than 10 weight percent fines were generated at the next highest pressure.

Different types of frac sand can bear different ranges of crush resistance (stress ranges) and are assigned classes recognized by API that reflect this (Herron, 2006). Class C sands (such as modern aeolian sands) have a stress range of 0–4,000 psi, Class D sands (such as the Hickory Sandstone Member of Riley Formation) have a stress range of 0–5,000 psi, and Class E sands (such as the St. Peter Sandstone) have a stress range of 2,000–6,000 psi (Herron, 2006). Modified and synthetic proppants have higher stress ranges than frac sand: resin-coated proppants will bear 4,000–12,000 psi, and ceramic proppants will bear 10,000–16,000 psi of stress loading (Herron, 2006).

Crush resistance of frac sand is dependent upon hardness of grain, with quartz being at a Mohs hardness of 7. It follows, therefore, that a high percentage of silica in the sand increases its crush resistance. Additionally, grain crystallinity, referring to either single crystals (monocrystalline) or composite grains (“clusters”) composed of cemented grains or multiple intergrown crystals (polycrystalline), impacts crush resistance because monocrystalline grains are stronger than composite grains (Zdunczyk, 2007). Other factors that enhance crush resistance include the absence of weak planes that may have occurred due to stress in tectonic or metamorphic terranes (Geology, 2013), the absence of deep pitting of grains, and the absence of authigenic overgrowths on quartz grains (Zdunczyk, 2007). To reduce the presence of weaker grains in frac sand, the API proppants standard for percent of clusters is ≤1.0.

Low Solubility

Solubility of a sandstone is determined by the amount of soluble cement or soluble mineral grains that it contains. Low solubility requires a high percent of silica, as quartz tends to be insoluble under normal conditions, becoming increasingly soluble when the pH exceeds nine and being insoluble in acids other than hydrofluoric (HF) (Missouri Department of Natural Resources, 2014). Frac sand solubility is measured by percent weight loss from a test in which a 5-gram sample of proppant is soaked in a 12/3 mixture of HCl (hydrochloric)/HF acids for 0.5 hour at 150 degrees Fahrenheit (°F), after which the sample is rinsed, dried, and reweighed (American Petroleum Institute and others, 2008). The API solubility standard for proppants is ≤3.0 percent weight loss.

Low Turbidity

Low turbidity is defined as the absence of clay, silt, or other fine grains and impurities. The amount of suspended particles or other finely divided matter is measured in scattered light in a formazin-based solution at 90° angles and is recorded in either formazin turbidity units (FTU) or the

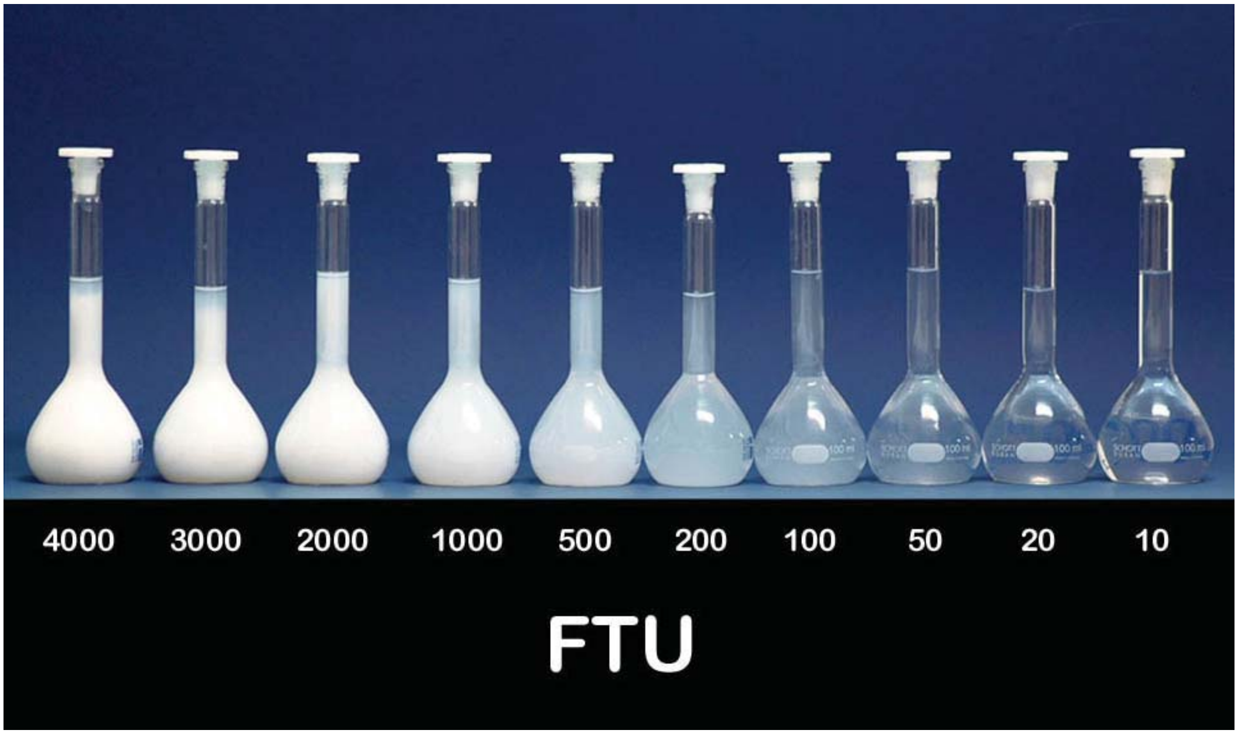


Figure 5. Turbidity, a measure of the amount of suspended particles and other finely divided matter. This is rated visually as illustrated by this typical series of formazin turbidity standards measured in formazin turbidity units (FTU) (used with permission from optek-Danulat, Inc., 2014).

roughly equivalent nephelometric turbidity units (NTU) (optek-Danulat, Inc., 2014). The API turbidity standard for proppants is ≤250 NTU, using a scale similar to the one shown in figure 5 (American Petroleum Institute and others, 2008).

Low turbidity is a result of mineralogical maturity and grain-size sorting in the natural depositional environment. Fine suspended matter in the mined sand is usually washed out during processing, so this property can be controlled for the final product (Zdunczyk, 2007; O’Driscoll, 2012; Buchsbaum, 2013).

Bulk Density and Specific Gravity Similar to Silica

Bulk density and specific gravity values that are similar to those for silica suggest high silica content for the sample. Bulk density is the density of both the proppant and the porosity, and it is measured by filling a known volume with dry proppant and measuring the weight. Apparent density excludes the extragranular porosity by placing a known mass in a volume of fluid and determining the amount of fluid that is displaced. Absolute density is the density that the material would have if no intragranular porosity were present (American Petroleum Institute and others, 2008).

Specific gravity of liquids and solids is defined as a dimensionless unit, which is the ratio of density of a material to the density of water at a given temperature. Specific gravity of quartz is 2.65 (Hurlbut, 1971).

The standard, ISO 13503-2, describes how density is measured but gives no requirement for frac sand. “Bulk density/specific gravity” is listed as an indicator of quartz purity of sand when its value is similar to that of quartz (Wolfe, 2013).

Ideal Frac Sand Deposit

Good Friability

Unconsolidated deposits of “soft, loose” sand or poorly consolidated, poorly cemented (friable) sandstone are most desirable (Runkel and Steenberg, 2012), as they do not need to be blasted during excavation or crushed during processing and can be mined by large excavators or power shovels (Maslowski, 2012). In some cases, blasting and crushing can cause fracturing of grains, resulting in increased angularity (reduced sphericity and roundness).

Near-Surface Access

The accessibility of a frac sand deposit at or near the surface reduces the cost of overburden removal (Runkel and Steenberg, 2012). Although most frac sand is mined from near the surface, surface access to the target zone is quite variable among frac sand source units and localities. Even in areas where the frac sand source is mapped as “exposed bedrock,” removal and protection of topsoil and subsoils must occur (Wisconsin Department of Natural Resources, 2012). Rarely, in western Wisconsin, where >100-ft-thick resistant dolomite overlies the Jordan Formation, frac sand is mined underground or is mined from active or abandoned dolomite quarries in the overlying formation (Runkel and Steenberg, 2012).

Proximity to Transportation Routes that Serve Petroleum Basins

Trucks are used to transport frac sand to the plant, to rail facilities, and sometimes directly to the customer (Zdunczyk, 2014). In some cases, where feasible, sand is delivered to the market downriver by barge (Wisconsin Department of Natural Resources, 2012). Rail is the preferred method of transporting sand from the mine or from the processing plant to the location of final use (Wisconsin Department of Natural Resources, 2012). Sand deposits that have ready access to trucking, river, and rail transportation routes that serve petroleum basins provide cost advantages for the operator.

Petroleum Industry Use of Frac Sand

Although the recent surge in frac sand mining has followed the expansion of drilling for tight shale gas, the consumption of frac sand more broadly includes all unconventional (tight) petroleum plays. Although most tight petroleum plays in North America are in shale basins (fig. 6), horizontal drilling and fracking also enhances production in oil and gas wells that penetrate low-permeability sandstones, carbonates, and coalbed methane reservoirs. Concurrent with the production of large shale gas plays, the production of oil from several tight reservoirs has also contributed to the increased demand for frac sand and other proppants.

The North American shale plays are commonly referred to by the names of the producing rock units and are located within differently-named subsurface structural basins (fig. 6). In the United States, the giant shale gas plays include the Barnett in the Ft. Worth Basin, the Fayetteville in the Arkoma Basin, the Haynesville in the Texas-Louisiana-Mississippi Salt Basin, and the Marcellus in the Appalachian Basin (Sandrea, 2014). The principal shale oil plays are the Bakken in the Williston Basin, the Avalon (or Avalon-Bone Spring) in the Permian Basin, the Barnett-Woodford in the Permian and Marfa Basins, and the Eagle Ford in the Western Gulf Basin (Sandrea, 2014). Although a shale gas play, shale oil play, or a tight sand oil play may be developed in a particular reservoir in a particular basin, unconventional petroleum basins are not all clearly defined as solely shale gas-producing or tight oil-producing basins. This is because the nature of the hydrocarbon production changes within the reservoir over time. A U.S. example of this is the Eagle Ford play in Texas, which began with dry gas production, followed by wet gas, and eventually by oil production from the same reservoir. Along this continuum, the same basic technologies (such as horizontal drilling and fracking) are used for tight oil and shale gas plays (Stark, 2012); therefore, proppant is needed in all cases.

In Canada, the principal tight (sandstone or shale) oil and shale gas reservoirs are in the western shale basins of Alberta and British Columbia and in the eastern shale basins of Quebec, Nova Scotia, and New Brunswick (Kuuskraa and others, 2011; Advanced Resources International, 2013). The estimated 2014 demand for frac sand for the Horn River and Montney Shale Basins of British Columbia is >4 million metric tons per annum (mtpa) (Stikine Gold, 2014). Although efforts are underway to supply the Canadian shale basins with domestic frac sand sourced from as far north as the Northwest Territories, most frac sand is imported from the United States or comes from Manitoba due to the higher quality of these sources, despite the greater transportation costs (Snyder, 2013).

In Mexico, tight oil and gas production is primarily from the Cretaceous Eagle Ford Formation that extends from south Texas and the Jurassic (Tithonian) shales that produce in the Burgos Basin (Kuuskraa and others, 2011). Future prospective units are in basins to the west and farther south (Kuuskraa and others, 2011; U.S. Energy Information Administration, 2011).

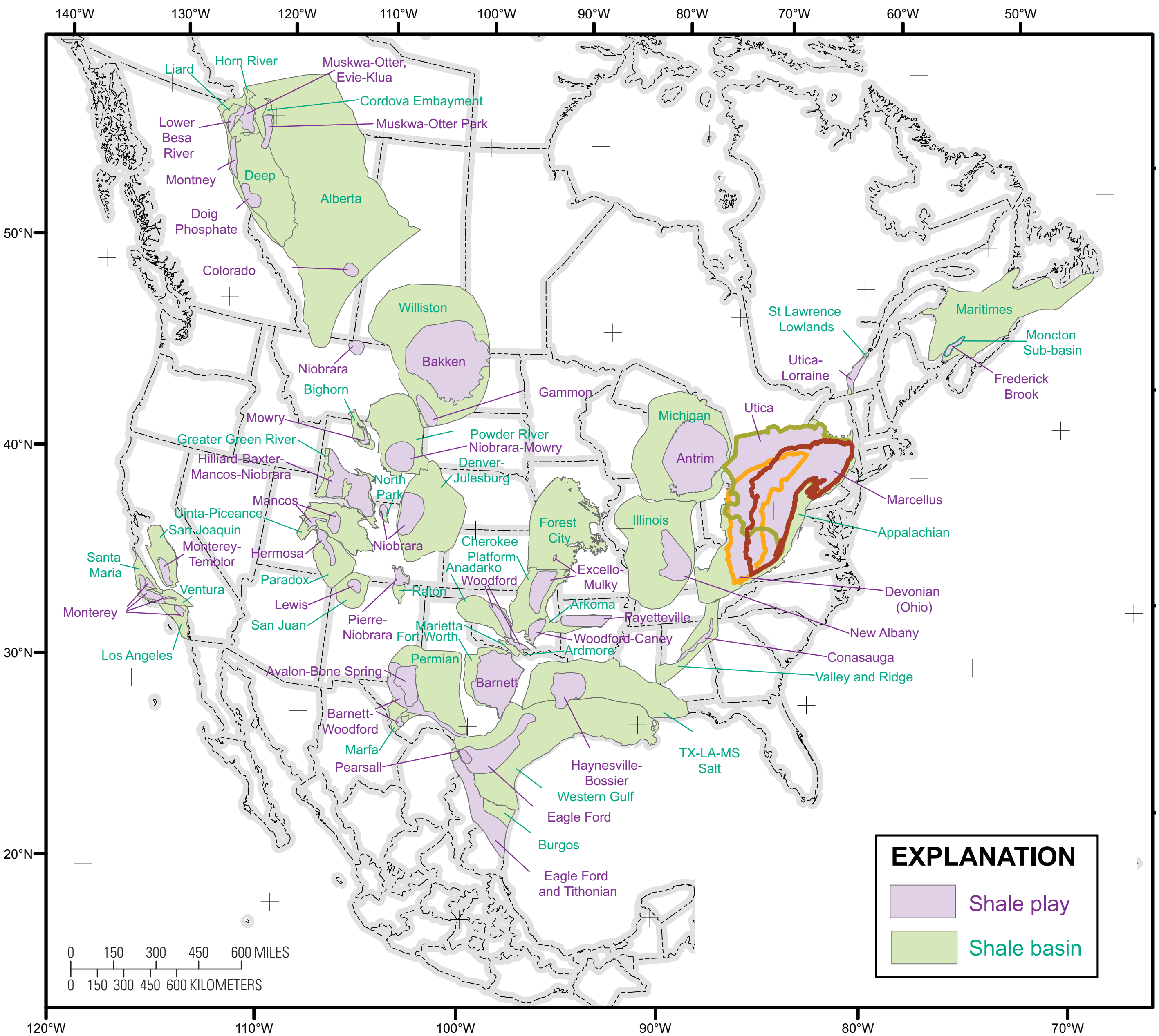
Outside North America, other shale gas basins and plays place additional demands on the global frac sand supply. Brazil, Argentina, Chile, Poland, France, Ukraine, Turkey, Morocco, Algeria, South Africa, Libya, China, and Australia are developing unconventional petroleum resources that use frac sand and other proppants (O’Driscoll, 2012).

Principal Producing Frac Sand Source Units in the United States

Brief Overview

The upper Midwest (north-central midcontinent) of the United States has the principal supply of the ideal frac sand that the industry calls “Northern White” or “Ottawa White” sand in near-surface exposures that make it economic to mine. This 99.8-percent pure silica sand is mined from the Middle and Upper Ordovician St. Peter Sandstone, the Upper Cambrian and Lower Ordovician Jordan Formation, and the Upper Cambrian Wonewoc and Mount Simon Formations in Wisconsin, Minnesota, Illinois, and nearby States (Zdunczyk, 2007; Runkel and Steenberg, 2012) (pl. 1). These units are widespread sheet sands deposited in the early Paleozoic continental interior seaway, whose lithologic characteristics and stratigraphic relationships are well illustrated in exposures in Sauk County, Wisconsin (Clayton and Attig, 1990) (fig. 7).

In the Sauk County, Wisconsin, example, the St. Peter Sandstone is an areally extensive marine coastal sandstone representing the onset of Sloss’s (1963) Tippecanoe sequence that was deposited on the deeply eroded unconformable surface of the Ordovician Oneota Dolomite (fig. 7) of the Prairie



Projection: USA_Contiguous_Albers_Equal_Area_Conic_USGS_version

Datum: D_North_American_1983

Figure 6. Map of shale plays and basins in North America (modified from Kuuskraa and others, 2011; U.S. Energy Information Administration, 2011). The plays are shown in lavender and the basins are in light green. Overlapping plays in the Appalachian Basin are distinguished by colored borders: Marcellus in red, Devonian (Ohio) in orange, and Utica in pea green.

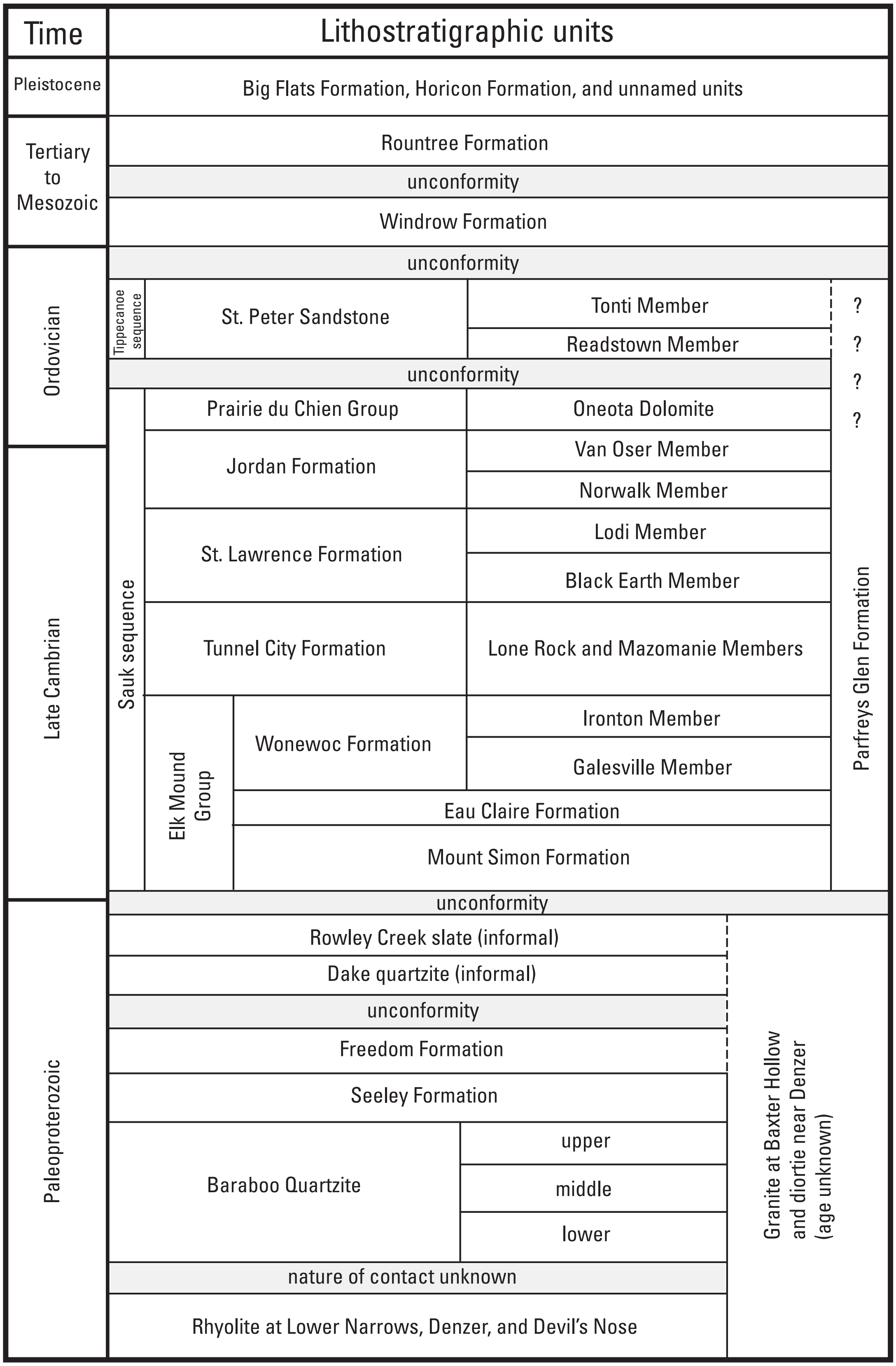


Figure 7. Geologic column showing the lithostratigraphic units in Sauk County, Wisconsin (modified from Clayton and Attig, 1990).

du Chien Group that forms the top of the Sauk sequence in Wisconsin (Sloss, 1963; Clayton and Attig, 1990). The underlying Upper Cambrian and Lower Ordovician Jordan and Upper Cambrian Wonewoc and Mount Simon units are among the widespread marine sands of the earlier phases of the Sauk sequence deposited on the unconformable Precambrian surface of the North American Craton (Clayton and Attig, 1990).

Although all four of these frac sand source units in the Midwest dominantly consist of fine- to coarse-grained quartzose sandstone, they vary relative to each other as to grain-size distribution (Runkel and Steenberg, 2012). Compared with the others, the St. Peter has a small percentage of 20/40 mesh sand and the highest percentage of sand finer than 100 mesh (Thiel, 1957; Ostrom, 1971). The Jordan (Van Oser Member) contains the highest percentage (40 percent) of the larger grain sizes of 20/40 mesh and the smallest percentage (<10 percent) of the least desirable >100 mesh sizes (Runkel, 1994b). The St. Peter, Jordan, and Wonewoc in both Minnesota and Wisconsin, are relatively consistent sources of 40/70 mesh sand (Theil, 1959; Ostrom, 1971). The Mount Simon is also a significant source of 20/40 and 40/70 mesh sand in Wisconsin (Ostrom, 1971).

In central Texas, deposits mined for frac sand are referred to as “Brown” or “Brady” sand. These are local quartz arenites that occur within the subarkosic to arkosic Upper Cambrian Hickory Sandstone Member of the Riley Formation in the Llano uplift region (Kyle and McBride, 2014) (fig. 8).

Oklahoma’s principal mined source of frac sand is the basal sandstone member of the Middle Ordovician Oil Creek Formation of the Simpson Group (fig. 9) that crops out in south-central Oklahoma (Suhm and Ethington, 1975). This sandstone unit is referred to as the Connell Sandstone Member in west Texas and has characteristics similar to the Middle and Upper Ordovician St. Peter Sandstone of the Mississippi Valley (Suhm and Ethington, 1975).

In addition to these six principal frac sand source units, the Upper Cambrian Lamotte Sandstone (a Mount Simon-equivalent) is a source of frac sand in Missouri. Also, Quaternary sand deposits that are being used as frac sand are Lake Michigan eastern shore sand and Arkansas River sand in Arkansas. These nine frac sand producing source units are subsequently described in greater detail as to their petrology, stratigraphy, areal extent, and paleoenvironmental characteristics. The units are organized by region and listed in order of relative importance as a frac sand source within each region.

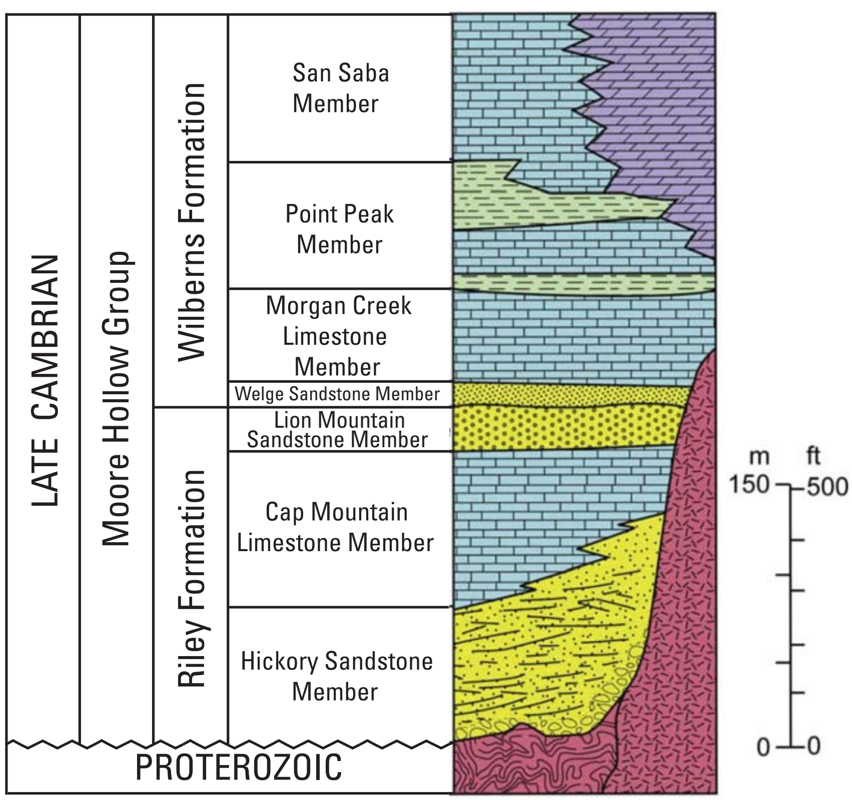


Figure 8. Stratigraphic column for the Upper Cambrian units of the Llano uplift of central Texas featuring the Hickory Sandstone Member (from Kyle and McBride, 2014; modified after Barnes and Bell, 1977).

Midwest Region

St. Peter Sandstone

The Middle and Upper Ordovician St. Peter Sandstone (fig. 7) and the partly stratigraphically equivalent sandstones of the Simpson Group (fig. 9) (see Oil Creek Formation section) are widespread in areal extent, both in the surface and subsurface, occurring in southern Wisconsin, Minnesota, Illinois, Iowa, Michigan, Indiana, Kentucky, Missouri, Nebraska, Kansas, Arkansas, Oklahoma (Dake, 1921; Dapples 1955; Cole, 1975; Mai and Dott, 1985; Davis, 2011), west Texas (Suhm and Ethington, 1975; Jones, 2009), and Ohio and Tennessee (Dake, 1921). The present distribution of the uneroded sandstones of the St. Peter and Simpson attests to the widespread original depositional extent that covered much of the midcontinent region (fig. 10).

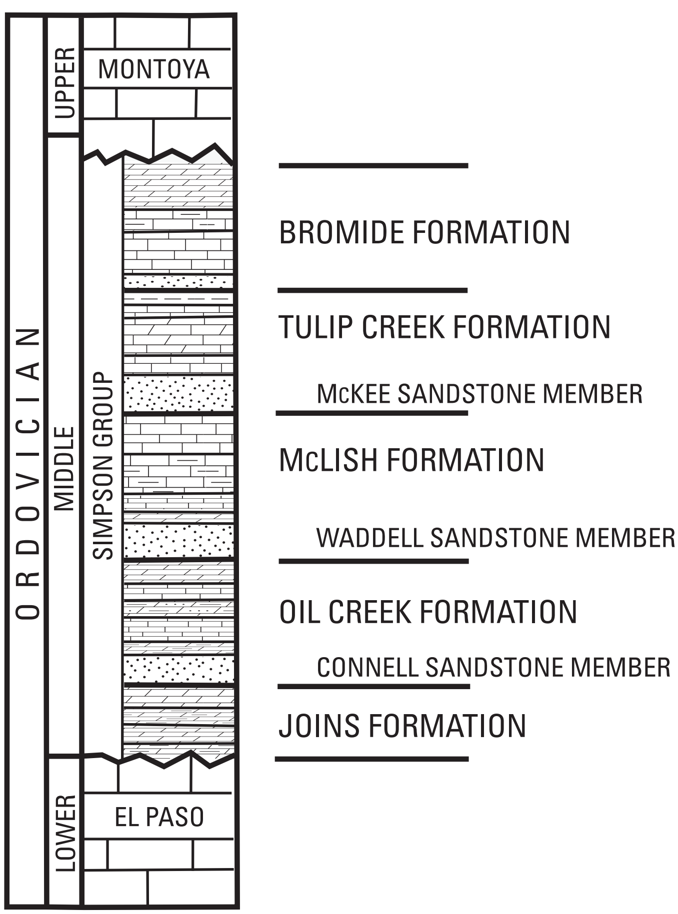


Figure 9. Formations and members of the Simpson Group in common usage in Oklahoma and west Texas (modified from Suhm and Ethington, 1975).

The St. Peter Sandstone occurs in the near-surface in parts of western, southwestern, and south-central Wisconsin, southeastern Minnesota, northeastern Iowa, northern Illinois (Mai and Dott, 1985) (fig. 11), and in central and southeastern Missouri (Harrison, 1997; Davis, 2011, 2014) and northern Arkansas (Glick and Frezon, 1953) (fig. 12). Partly equivalent Oil Creek Formation is recognized in outcrops of eastern Oklahoma (Buttram, 1913). The unit lies deeper in the subsurface in eastern Kansas (Leatherock, 1945; Dapples, 1955), eastern Wisconsin (Mai and Dott, 1985), Michigan (Mai and Dott, 1985; Barnes and others, 1996), and eastward to Indiana, Ohio, Kentucky, and Tennessee (Dake, 1921).

The St. Peter Sandstone was initially described from outcrops at Fort Snelling in Bloomington, Hennepin County, Minnesota, where exposures of the upper member can still be observed along the Minnesota River (formerly, the St. Peter's River) (Mossler, 2008). In southeastern Minnesota, the St. Peter unconformably overlies the Ordovician Shakopee Formation, which unconformably overlies the Oneota Dolomite (Mossler, 2008). In areas of Wisconsin and elsewhere in the Midwest, the St. Peter directly overlies the eroded surface of the Oneota Dolomite, which is regarded as the boundary between the Sauk and Tippecanoe sequences of Sloss (1963) that represents a prolonged depositional hiatus (Mossler, 2008). The St. Peter is overlain by the Glenwood Formation, but the nature of the contact is inconclusive (Mossler, 2008). Along the Wisconsin arch in Wisconsin and northern Illinois, the St. Peter Sandstone and Glenwood Formation are recognized as formations of the Ancell Group (Mai and Dott, 1985; Shaw and Schreiber, 1991). Wisconsin State maps place the St. Peter Sandstone into the Ancell Group (Ostrom, 1971; Mudrey and others, 1982; Brown, 1988), although Clayton and Attig (1990) do not recognize the Ancell Group in Sauk County.

From outcrops in Sauk County, Wisconsin, the St. Peter Sandstone is subdivided, in descending order, into the Tonti and Readstown Members (Clayton and Attig, 1990) (fig. 7). In this area, the younger Tonti Member makes up most of the St. Peter Sandstone and consists of very pale brown to yellowish red, fine- to medium-grained, quartzose sandstone, the coarser grains of which tend to be rounded, but in many places the grains exhibit faceted quartz overgrowths that produce a conspicuously sparkly surface on outcrop (Clayton and Attig, 1990). Where it occurs in outcrop, the sandstone is hard due to the presence of silica cement (Clayton and Attig, 1990). The Readstown Member, by contrast, is a breccia of pebbles, cobbles, and boulders of sandstone that resembles that of the overlying Tonti Member (Clayton and Attig, 1990).

In the area from north-central Illinois to southeastern Missouri, the subdivisions of the St. Peter include the fine-grained sandstone of the Tonti Member as the lower unit and the medium-grained sandstone of an overlying member known as the Starved Rock Member (Visocky and others, 1985). North of Jefferson County, Missouri, fine- to coarse-grained, pink to reddish-brown sandstone with varying amounts of shale, chert, and dolomite fragments constitute a basal unit that underlies the Tonti Member that is referred to as the

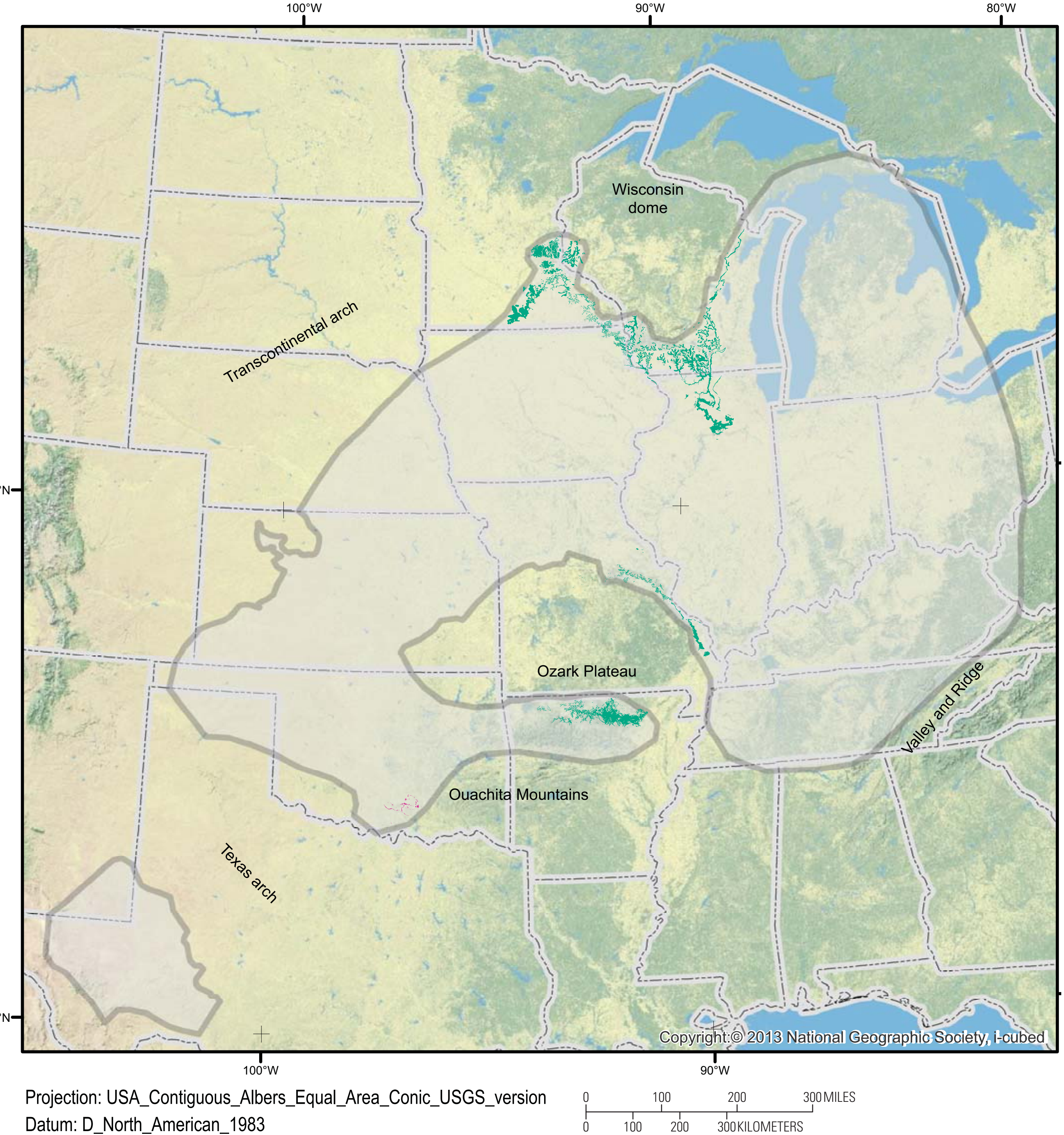


Figure 10. Surface and subsurface areal extent (translucent areas inside gray outlines) of the St. Peter Sandstone (outcrops in dark green) in the upper and central Midwest and partly equivalent units within the Simpson Group such as the Oil Creek Formation in Kansas, Oklahoma (outcrops in pink), and west Texas (modified from Dake, 1921; Dapples, 1955; Cole, 1975; Jones, 2009; Davis, 2011).

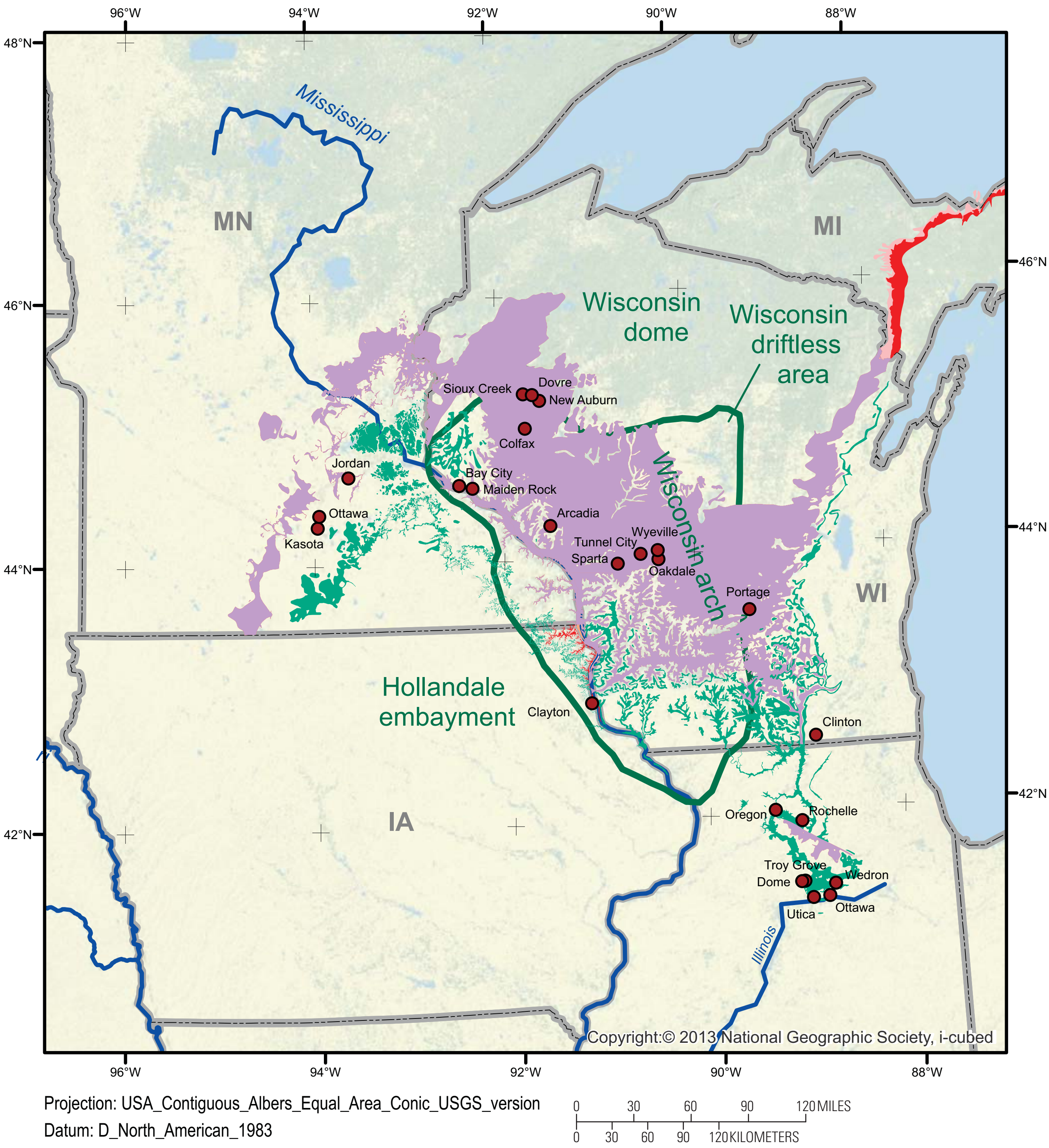
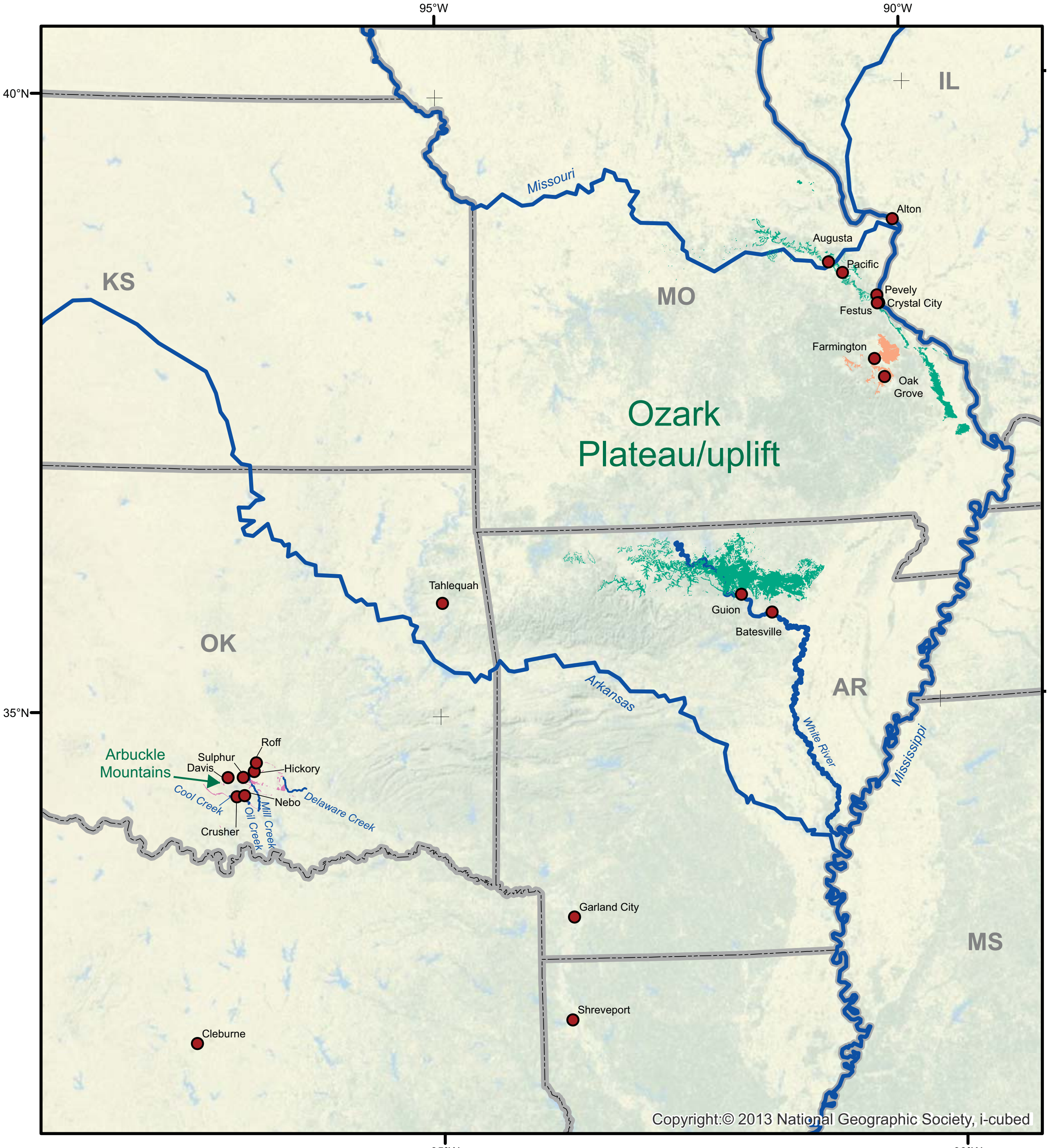


Figure 11. Surface exposures of frac sand source units in the upper Midwest. Shown are the St. Peter Sandstone (green); the Cambrian, undivided (lavender) that includes the Jordan, Wonewoc, and Mount Simon Formations; the Jordan Formation in Iowa and its equivalent Trempealeau Formation in Michigan (red), the Wonewoc Formation in Iowa and its equivalent Munising Formation in Michigan (pink); and the Mount Simon Formation in narrow outcrops in extreme northeastern Iowa (orange). (Red dots are towns referenced in the text.)



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0 30 60 90 120 MILES
0 30 60 90 120 KILOMETERS

Figure 12. Surface exposures of frac sand source units in the central Midwest. Shown are the St. Peter Sandstone (green) in Missouri and Arkansas, the Oil Creek Formation (pink) of the Simpson Group (a partial equivalent of the St. Peter Sandstone) in eastern Oklahoma, and the Lamotte Sandstone (orange) (an equivalent of the Mount Simon Formation) in southeastern Missouri. (Red dots are towns for reference.)

Kress Member (Suter and others, 1959). In some parts of the subsurface of northern Missouri, the Kingdom Shale Member separates the Tonti and Starved Rock Members (Missouri Department of Natural Resources, 2014).

The St. Peter Sandstone has been partially correlated with sandstone as far south and west as the Simpson Group of Oklahoma and west Texas (Suhm and Ethington, 1975). In northeastern Oklahoma, subsurface subdivisions of the Simpson Group in stratigraphic (ascending) order are the Burgen Sandstone, the Tyner Formation, and two upper members referred to in oil field terminology as the "Wilcox" sand and the post-"Wilcox" sand (White, 1926). The Burgen Sandstone is recognized in outcrops of eastern Oklahoma (Buttram, 1913). Although it was proposed by Purdue and Miser (1916) that the St. Peter grades into the sandy carbonates of the underlying Everton Formation farther southward, the well-rounded frosted-grained sandstone unit within the Everton Formation was later distinguished as the Newton Sandstone Member of the Everton in northern Arkansas (McKnight, 1935), where the St. Peter was found to overlie the Everton (Glick and Frezon, 1953).

In Missouri, the St. Peter Sandstone has been extensively quarried for silica in the St. Louis area (Harrison, 1997). Excellent exposures of the St. Peter are common near Pacific, Missouri, where the unit played a prominent role in glass manufacturing (Davis, 2014) (fig. 13).

In this area, the St. Peter Sandstone has been described as an ultra-pure (>99 weight percent silica in places), well-sorted, friable, fine- to medium-grained, rounded, highly spherical, and characteristically frosted quartzose sandstone (Davis, 2014; Missouri Department of Natural Resources, 2014) (table 1).

In northwestern Wisconsin, the St. Peter Sandstone is 25 meters (m) (82 ft) thick (Mudrey and others, 1987). Elsewhere, the formation thickness is highly variable. In Missouri, the St. Peter Sandstone thickness averages 80 to 100 ft (24 to 30 m) (Missouri Department of Natural Resources, 2014). In most of northern Illinois, it ranges from 100 to 200 ft (30 to 60 m) thick, reaching a maximum thickness range of 400 to 600 ft (120 to 180 m) north of the Sandwich fault zone (Visocky and others, 1985). The highly variable thickness is the result of deposition on both erosional channels and karsted surfaces in the underlying carbonate beds (Visocky and others, 1985). In the persistently subsiding paleo-Michigan Basin, the St. Peter Sandstone, also known as the Bruggers Sandstone (Catacosinos and others, 2001), reaches a maximum thickness of 1,200 ft (366 m) in the basin center where the complete Lower and Middle Ordovician sequence is represented (Barnes and others, 1996).

Despite bearing the industry name "Northern White," the St. Peter can be white to pale yellow, buff to tan, depending upon its iron content, and still maintain its high silica content (Mudrey, and others, 1987). Commonly in exposures in Missouri, bedding within the St. Peter Sandstone is indistinct, and the unit may be described as massive throughout (Davis, 2014) (fig. 13). Locally, however, the rock may reveal cross bedding and ripple marks and is generally porous, permeable, and mostly nonfossiliferous in Missouri (Missouri Department of Natural Resources, 2014). Marine fossils are observed in the unit, however, as far north as Minneapolis, Minnesota (Dake, 1921).

The general mineralogic and textural maturity of the St. Peter Sandstone is attributed to multicyclical marine shoreface and coastal aeolian processes acting upon sediment (Dott, 2003) derived from older Cambrian and Proterozoic sandstones or distant basement rock (Dake, 1921; Tyler, 1936). Dake (1921) suggested that the Upper Cambrian Potsdam Sandstone was a possible late-stage source for the St. Peter Sandstone. Revised to the Potsdam Supergroup in the subsurface, this unit includes the Mount Simon Formation and the Munising Group that contains the Galesville Member of the Wonewoc Formation (Droste and Patton, 1985). Uranium-lead (U-Pb) isotopic analyses of detrital zircon and samarium-neodymium (Sm-Nd) in quartz indicate a mixed crystalline basement provenance for the lower Paleozoic sheet sandstones of the midcontinent and show that the proportions from each source vary across the depositional extent of each unit (Johnson and Winter, 1999). Detrital zircon geochronology data show that the St. Peter Sandstone in Wisconsin was largely derived from the reworked Upper Cambrian Galesville Member of the Wonewoc Formation whose likely provenance was crystalline basement of the Archean Superior Province and the Grenville orogeny (Johnson and Winter, 1999; Konstantinou and others, 2014). Owing to variable proximity to sediment sources, the St. Peter Sandstone in Michigan contains a greater proportion of sediment from the Grenville Province relative to the St. Peter in Wisconsin (Johnson and Winter, 1999; Konstantinou and others, 2014).

Similar to variability in sediment source across its depositional extent, the St. Peter Sandstone is not homogeneous as to the impact of diagenetic alteration upon mineralogic purity, grain size, grain shape, and friability. For example, quartz overgrowths are observed in the unit in areas of southwestern and south-central Wisconsin and in southeastern Minnesota (Winfree, 1983; Clayton and Attig, 1990; Kelly, 2006; Kelly and others, 2007) making the grains less rounded and less spherical in places.

Jordan Formation

The Upper Cambrian and Lower Ordovician Jordan Formation is a marine sandstone that conformably overlies the Lodi Member of the St. Lawrence Formation and unconformably underlies the Lower Ordovician Oneota Dolomite (Clayton and Attig, 1990; Mossler, 2008) (fig. 7). The Jordan Formation is at or near the surface in parts of Wisconsin, southeastern Minnesota, northeastern Iowa (Ostrom, 1966; Clayton and Attig, 1990), and northern Illinois (Clayton and Attig, 1990) (fig. 11). It is present in the subsurface of central Iowa and northwestern Illinois (Kapchinske, 1980). The unit is also referred to as the Jordan Sandstone in Wisconsin, Minnesota, and Iowa (Thomas, 1992; Runkel, 1994a); as the Jordan

Figure 13. Outcrop of dune facies of St. Peter Sandstone at old mine entrances in Pacific, Missouri, where it is still actively quarried nearby. (Image attribution: by Kbh3rd at en.wikipedia [Public domain], from Wikimedia Commons.)

Table 1. Properties of St. Peter Sandstone in Missouri (Missouri Department of Natural Resources, 2014).

Color	White, with occasional shades of pink and green. Weathered surfaces are a dirty gray or brown and hardened at many localities.
Grain size	<0.075 millimeter (mm) (No. 200 U.S. Standard Sieve Series size) to 2 mm (No. 10 U.S. Standard Sieve Series size)
Hardness	Individual sand grains are hard, seven on Mohs scale.
Cementation	Soft, friable, easily disaggregated
Specific Gravity	Estimated 2.24 assuming 15 percent porosity (specific gravity of quartz is 2.65)
Porosity	Estimated 10–15 percent
Solubility	Quartz has a very low solubility under normal conditions, thus St. Peter Sandstone is stable in ordinary situations. The solubility of quartz increases rapidly when pH exceeds nine. Quartz is insoluble in acids except hydrofluoric.

Sandstone of the Trempealeau Group in Wisconsin (Ostrom, 1978); and as the Jordan Sandstone Member of the Trempealeau Formation in the Upper Peninsula of Michigan (Michigan Department of Natural Resources, 1987). The unit was deposited during the late Trempealeau interval of St. Croixan time (Ostrom, 1966, 1967). The Jordan of southeastern Minnesota, west-central Wisconsin, and northeastern Iowa was restricted in age to Late Cambrian and determined to be a marine regressive sandstone (Thomas, 1992; Runkel, 1994a, 1998).

Throughout much of Wisconsin, the Jordan Formation contains primarily two quartzose sandstone members (fig. 7) (Mudrey and others, 1987; Brown, 1988; Clayton and Attig, 1990; Runkel, 1994a). The uppermost unit is the Van Oser Member, which is quartzose, white to brown to yellow or orange, fine to medium grained, poorly sorted, medium to thin bedded, cross bedded, with calcite-cemented nodules, is iron cemented in places, may be locally interbedded with the underlying unit, and is 9 to 15 m (30 to 49 ft) thick (Mudrey and others, 1987). In extreme western Wisconsin, the Van Oser is a medium- to coarse-grained, well-rounded, easily disaggregated quartz arenite that is thick-bedded, contains cross-bedding and calcareous concretions, and is about 45 ft (14 m) thick (Ostrom, 1987). The Van Oser is interpreted as a higher energy, marine intertidal sand deposited as the sea shallowed (Runkel, 1994a). Underlying the Van Oser Member, the Norwalk Member is a quartzose, white, fine-grained, rounded, moderately-sorted, medium-bedded sandstone with a trace of garnet, and a thickness of 15 to 18 m (49 to 59 ft) (Mudrey and others, 1987). In extreme western Wisconsin, the Norwalk is a fine- to very fine-grained feldspathic sandstone (Ostrom, 1987; Runkel, 2000). It is interpreted as a low-energy, below wave base, marine deposit (Runkel, 1994a).

The Van Oser Member is the more suitable of the Jordan subunits in Wisconsin for frac sand mining, being coarser grained and higher in silica than the Norwalk Member (Runkel and Steenberg, 2012; Brown, 2014). The Van Oser is highly prized for its high yield of 20/40 mesh quartz sand (Runkel and Steenberg, 2012). An important consideration when mining the Van Oser sandstone is the approximately 100-ft (30-m)-thick resistant Oneota Dolomite of the Ordovician Prairie du Chien Group that exists as overburden in many places in Wisconsin (Runkel and Steenberg, 2012). For this reason, the Van Oser is extracted from hilltops in Barron and Chippewa Counties; from old quarries and ridgetops in Dunn, St. Croix, and Buffalo Counties; and from underground mines in Pierce County, Wisconsin (Brown, 2014).

In southeastern Minnesota, the Van Oser Member is interfingered with the Waukon Member (also of the Jordan Formation) and is overlain by the Sunset Point Member of the Jordan (Ostrom, 1987), which is a fine-grained feldspathic and dolomitic shallow marine deposit (Thomas, 1992) now referred to the Coon Valley Member of the overlying Oneota Dolomite (Runkel, 1994a). Similarly to the subdivisions in Wisconsin, the Van Oser Member in Minnesota is described as a medium-grained quartzose sandstone, and the Norwalk and Waukon Members are very fine-grained feldspathic sandstones (Thomas, 1992).

In parts of Minnesota and western Wisconsin, diagenetic processes such as quartz syntaxial and potassium feldspar epitaxial overgrowths, hematite precipitation, dolomitization, calcite precipitation, calcite dissolution, and a second hematite precipitation have variously altered the original texture of the sandstone of the Jordan Formation (Thomas, 1992; Runkel and Steenberg, 2012). Samples from Arcadia, in Trempealeau County, Wisconsin, show originally rounded quartz grains with second-stage rounding of quartz overgrowths indicative of multicycling, and authigenic feldspar overgrowths that result in localized compromises to optimal frac sand properties (Runkel and Steenberg, 2012).

Wonewoc Formation

The Upper Cambrian Wonewoc Formation is the uppermost formation within the Elk Mound Group (Clayton and Attig, 1990) (fig. 7). The formation overlies the Eau Claire Formation, also of the Elk Mound Group. In the upper Mississippi River valley, the Wonewoc Formation is a stratigraphically complex cratonic sheet sand that was deposited from a continuously abundant supply of sand in a relatively stable, slowly and uniformly subsiding low-relief basin (Hollandale embayment) under fluctuating sea level conditions during the Sauk II and Sauk III subsequences of Palmer (1981) (Runkel and others, 1998). The Wonewoc Formation is observed in southern Wisconsin, Michigan, Illinois, Indiana, Minnesota, and Iowa (Clayton and Attig, 1990) and in northeastern Nebraska (Runkel and others 1998). Although the Wonewoc bedrock is exposed in areas of Wisconsin, Minnesota, Iowa, and Illinois (fig. 11, pl. 1); the unit is mapped as Cambrian "undivided" in these States except for Iowa, which means the Wonewoc is combined with other Cambrian units, as described above for the Jordan.

Where it crops out in west-central Wisconsin, the Wonewoc Formation consists of two quartzose sandstone members. In descending order, they are the Ironton Member and the Galesville Member (fig. 7) (Mudrey and others, 1987; Brown, 1988; Clayton and Attig, 1990). In northeastern Wisconsin, the narrow outcrop belt of the Wonewoc Formation extends northward into the Upper Peninsula of Michigan, where it is known as the equivalent Munising Formation (Dott and others, 1986; Catacosinos and others, 2000). In the subsurface of the Upper Peninsula and the Michigan Basin, the unit is referred to as the Munising Group and contains a formation known as the Galesville Sandstone, (Catacosinos and others, 2000).

In much of Wisconsin, the Ironton Member is a quartzose, white to brown with iron staining, medium- to coarse-grained, subrounded, poorly sorted, wavy-bedded, vertically burrowed, calcite-cemented, 5-to 18-m (16- to 59-ft)-thick sandstone (Mudrey and others, 1987). Underlying the Ironton Member, the Galesville Member is a quartzose, white, fine- to medium-grained, rounded to subrounded, well-sorted, thick-bedded, cross-bedded, poorly cemented, 5- to 18-m (16- to 59-ft)-thick sandstone with individual bedding units 3 to 5 m (10 to 16 ft) thick (Mudrey and others, 1987). Wherever the sandstone of the Galesville is differentiated as a member, it is the prospective frac sand source within the Wonewoc Formation.

Although the Wonewoc Formation consists of highly pure silica sandstone, it is finer in average grain size than the Van Oser Member of the Jordan Formation, so it is relatively less suitable as a frac sand (Brown, 2014). Despite the relatively finer grain size, the Wonewoc can be mined for multiple markets that serve non-frac uses for the finer fraction as well as the frac sand market for the smaller proportion of coarser grained fraction (Brown, 2014). The extensive surface exposure of the Wonewoc is encouraging the development of new frac sand mines that target the Wonewoc sandstone in Trempealeau, Dunn, Buffalo, Jackson, and Monroe Counties, Wisconsin (Brown, 2014). The Chapel Rock Member of the correlative Munising Formation in Upper Peninsula, Michigan, has been considered for use as a potential glass sand because of its >98 percent quartz content (Heinrich, 2001), although it has not yet been targeted as a current source for frac sand.

Mount Simon Formation

The Upper Cambrian Mount Simon Formation is the basal unit of the Elk Mound Group (fig. 7) whose type section near Eau Claire, Wisconsin, is 234 ft (71 m) of mostly medium- to coarse-grained sandstone overlying Proterozoic granite and underlying the very fine- and fine-grained sandstone and shale of the Eau Claire Formation (Mossler, 2008). Throughout the upper Mississippi River valley, the Mount Simon Formation is an early representative of the Sauk sequence (Sloss, 1963) that directly overlies a variety of Proterozoic basement rocks (Morey, 1972). Commonly exposed in Wisconsin is an apparently extensive regolith beneath the Mount Simon Formation that is evidence for a prolonged period of weathering prior to its deposition (Ostrom, 1966). Evidence of a well-developed regolith over granite that underlies the Mount Simon Formation was also observed in the subsurface near Monticello in Wright County, Minnesota (Morey, 1972).

The Mount Simon Formation has been identified in southern Wisconsin, Illinois, Indiana, Kentucky, Ohio, Minnesota, and Iowa (Clayton and Attig, 1990). The formation is observed at the surface in southeastern Minnesota (Mossler and Book, 1984), Wisconsin (Mudrey and others, 1982), and Iowa (Witzke and others, 2010) (fig. 11, pl. 1), but it, too, is mapped in these States as Cambrian “undivided,” with the exception of Iowa. In the subsurface, the Mount Simon is an important aquifer for the Midwest (Young, 1992). From its erosional boundary in northern Wisconsin and southeastern Minnesota, the Mount Simon thickens southward to maximums of more than 2,000 ft (610 m) in central and north-central Iowa and 2,600 ft (790 m) in northeastern Illinois (Young, 1992), where it is the thickest subsurface formation in the Illinois Basin (Bell and others, 1964). The unit is recognized only in the subsurface of the Michigan Basin (Cottingham, 1990) where it reaches a thickness of more than 1,000 ft (305 m) along the basin’s western flank (Catacosinos, 1973). The Mount Simon Formation is present in the subsurface in Indiana where it is identified as part of the Potsdam Supergroup (Droste and Patton, 1985). The Mount Simon is also known in the subsurface of northern Missouri where it grades southward into the Lamotte Sandstone as the unit emerges along the flanks of the Ozark uplift (fig. 12, pl. 1) (Houseknecht and Ethridge, 1978).

In the northwest quadrant of Wisconsin, the Mount Simon Formation contains three informal quartzose sandstone units (Mudrey and others, 1987). The uppermost sandstone is quartzose, feldspar-bearing, white to light gray to pale brown, medium to course grained, angular, medium bedded, locally lenticular bedded, and at least 52 m (170 ft) thick (Mudrey and others, 1987). Beneath this unit is the second sandstone that is quartzose, pale yellow orange to pale gray orange, very fine grained, thin to medium bedded, angular, limonite cemented, and 38 m (125 ft) thick (Mudrey and others, 1987). This unit is underlain by an 18-m (60-ft)-thick, gray to pale-orange, silty shale (Mudrey and others, 1987). A basal sandstone unit is quartzose, very pale orange, very fine to fine grained, subangular to subrounded, and at least 35 m (115 ft) thick, but it is known only in the subsurface in northwestern Wisconsin (Mudrey and others, 1987).

In the west-central quadrant of Wisconsin, the Mount Simon crops out in parts of Dunn, Eau Claire, and Chippewa Counties where it is described as an undivided unit consisting of sandstone, pebble conglomerate, and shale (Brown, 1988). The sandstone is coarse to fine grained, gray to light brown to white, poorly sorted, thin to thick bedded, and locally feldspathic, with a maximum thickness of 70 m (230 ft) (Brown, 1988).

Farther eastward in Wisconsin, the Mount Simon is near the surface in Clark, Wood, northern Jackson, and Monroe Counties (Brown, 1988, 2014). Much of the sandstone of the Mount Simon Formation in this area has been reworked and deposited as alluvial sand that is mined as a byproduct of cranberry bog construction (Brown, 2014).

In the Wisconsin Dells area in Sauk County (south-central Wisconsin), the Mount Simon Formation is generally described as a medium-grained sandstone that contains a considerable amount of coarse and a smaller amount of fine grains; the coarser grains especially having undergone considerable rounding and consisting largely of quartz (Clayton and Attig, 1990).

The Mount Simon Formation extends into the subsurface as far east as western Ohio where it is described as tan, friable, moderately-sorted, rounded, coarse- to very coarse-grained, siliceous quartz arenite with minor heterolithic sandstone-mudstone couplets (rhythmites) and a quartz granule conglomerate (Saeed and Evans, 2012).

Lamotte Sandstone

In southeastern Missouri, the Upper Cambrian Lamotte Sandstone (a stratigraphic equivalent of the Mount Simon Formation of the upper Midwest) crops out near Farmington and Oak Grove, in the St. Francois Mountains of the Ozark uplift (fig. 12, pl. 1) (Houseknecht and Ethridge, 1978), where it is described as a soft, friable white sandstone, sometimes yellow or brown at surface, with a minimum thickness of 250 ft (76 m) (Winslow, 1894). Elsewhere in Missouri (Wilson, 1922; Young, 1992), Kansas (Moore and others, 1951; Cole, 1975), Oklahoma (Ireland and Warren, 1946), and Colorado (Maher, 1946), the Lamotte is present only in the subsurface, and may extend farther southward as the Reagan Sandstone of Oklahoma and Hickory Sandstone Member of the Riley Formation of Texas (Branson, 1944). In the subsurface, the Lamotte is described as a well-bedded, coarse- to fine-grained, yellow, gray, or brown friable sandstone with shale and conglomerate lenses and transitional greenish dolomite beds near the top and a thickness of 50 to 400 ft (15 to 122 m) (Wilson, 1922). The Lamotte is a basal sandstone that unconformably overlies Proterozoic crystalline basement and conformably underlies the Upper Cambrian Bonneterre Formation (Wilson, 1922), which is considered a stratigraphic equivalent of the Eau Claire Formation of the upper Midwest west of Illinois (Willman and others, 1975).

Lake Michigan Shore Sand

The Midwest is not only home to the four principal lower Paleozoic frac sand sources, but it also hosts unusually pure Quaternary dune sand deposits on the eastern shore of Lake Michigan that are mined for silica, some of which is used for frac sand (Sargent Sand, 2014). Sargent Sand Company, located north of Ludington (pl. 1) in Mason County, Michigan, produces from these Lake Michigan shore sands a highly crush resistant 30/70, 30/50, 40/70, and 100 mesh frac sand that meets or exceeds API specifications (Sargent Sand, 2014). The sand that is suitable for frac sand at this mine represents only a small portion of the glacially reworked aeolian deposits along the lake shore and is not featured as a mapped unit in this report.

Arkansas River Sand

Modern fluvial sands dredged from along the Arkansas River in Sebastian County, Arkansas, are being mined and marketed by Arkhola Sand and Gravel Company as frac sand. Quaternary deposits adjacent to the Arkansas River in eastern Pulaski County are mined by Delta Company (Encyclopedia of Arkansas, 2014). These deposits occur in several places along the Arkansas River in western and central Arkansas (fig. 12, pl. 1) and are not featured as mapped units in this report.

South-Central Region

Hickory Sandstone Member

The Hickory Sandstone Member is the basal member of the Upper Cambrian Riley Formation of the Moore Hollow Group (fig. 8) of central Texas that was deposited on the unconformable surface of the Proterozoic and crops out along the western flank of the Llano uplift (Kyle and McBride, 2012) (fig. 14, pl. 1).

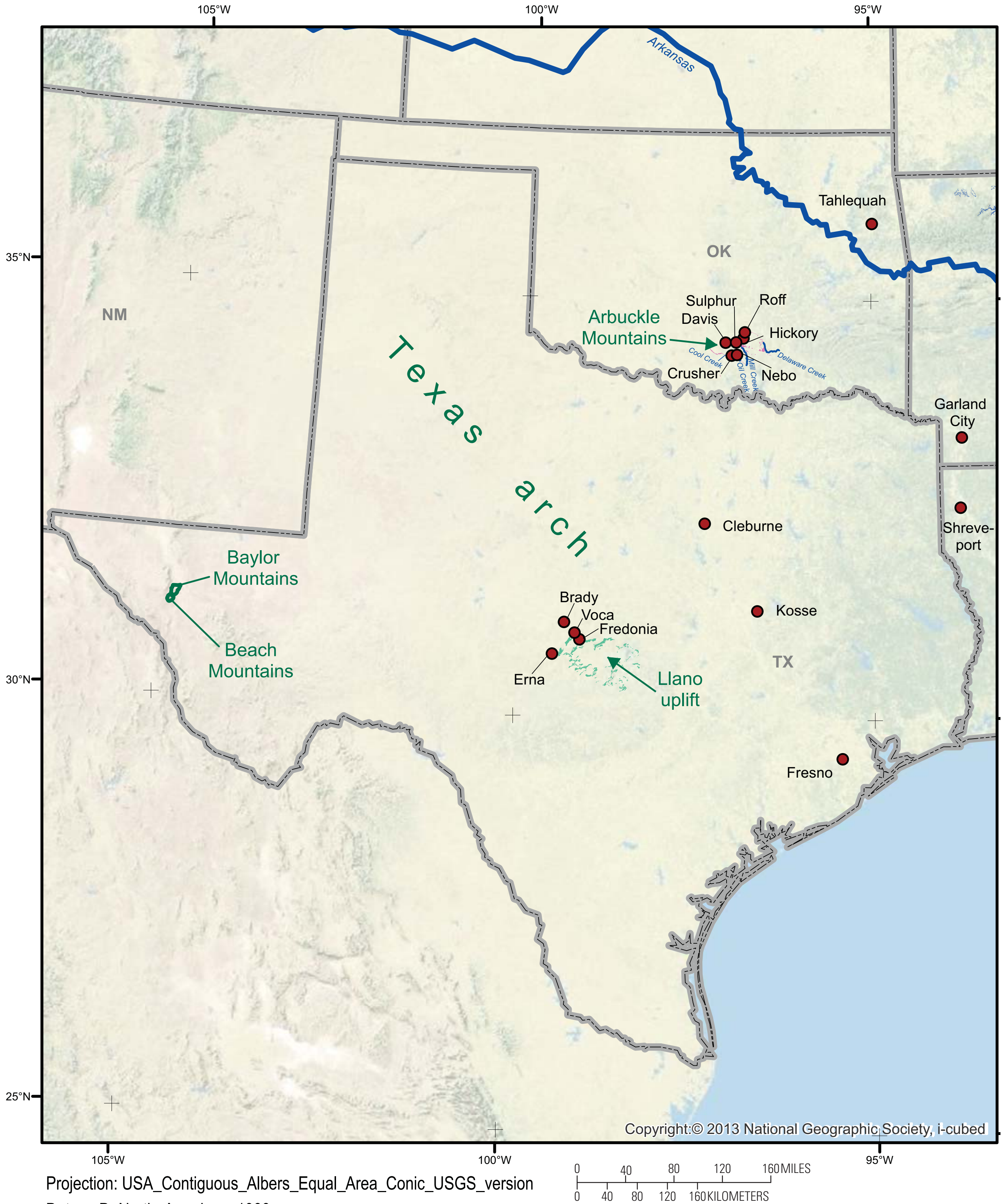
Frac sand that is referred to as “Brown” or “Brady” sand is mined from local quartz arenites that occur within the marine subarkosic to arkosic Upper Cambrian Hickory Sandstone Member (Kyle and McBride, 2012) (fig. 8). In the Voca area of Texas, sand production is generally from a 50- to 65-ft (15- to 20-m) near-surface lower interval of the Hickory Sandstone Member (Kyle and McBride, 2012). The level of suitability of this sand as a proppant results from the combination of its depositional, burial, and diagenetic histories. The marine transgressive sands of the Hickory Member were derived from the Precambrian basement rocks and deposited on an extensive unconformity (Kyle and McBride, 2012). Although the original source rocks had a high feldspar content, some of the arkosic sandstones that first formed underwent diagenetic alteration that removed the feldspars, resulting in an elevated quartz content (Kyle and McBride, 2012). Some of the sandstone of the Hickory Member was reworked from older fluvial deposits and aeolian dunes and was redeposited as quartz arenites that have well-sorted and well-rounded grains (Kyle and McBride, 2012). Furthermore, the sandstones remained friable near the Llano uplift, where they were never buried deeper than 1,500 ft (about 1 km) (Kyle and McBride, 2012). Compared to the more suitable “Ottawa” or “Northern White” frac sands, these “Brown” or “Brady” sands have a higher percentage of coarser grades (8/16, 12/20, and 16/30 mesh) (Texas Silica, 2014a). Also, rather than consisting of monocrystalline quartz, they are polycrystalline quartz grains, which makes them less crush resistant than the “Ottawa” sands (Levson and others, 2012).

Oil Creek Formation

The Middle Ordovician Oil Creek Formation is one of five formations within the Simpson Group (Wright, 1965; Suhm and Ethington, 1975) (fig. 9) that were deposited in the Permian Basin of west Texas and southeast New Mexico and in Anadarko Basin of Oklahoma (Jones, 2009) (fig. 6).

The southernmost depocenter for the Simpson Group was a broad, shallow, gently dipping depression referred to as the Tobosa Basin, a tectonic basin that was the precursor to the Permian Basin (Galley, 1958; Adams, 1965; Wright, 1965; Jones, 2009) (pl. 1). At the time of Simpson Group deposition, the Tobosa Basin was separated from the Anadarko Basin by a

Figure 14. Surface exposures of “Brady” or “Brown” frac sand source units in central Texas and other less premium frac sand outcrops in Oklahoma. Shown are the Upper Cambrian Hickory Sandstone Member (light green) of the Riley Formation in the Llano uplift area of central Texas and the Middle Ordovician Oil Creek Formation (pink) of the Simpson Group—a partial equivalent of the St. Peter Sandstone. (Red dots are towns mentioned in the text.)—Following page



Projection: USA_Contiguous_Albers_Equal_Area_Conic_USGS_version

Datum: D_North_American_1983

peninsula that was an extension of the Transcontinental arch, also referred to as the Texas arch (Wright, 1965; Jones, 2009). The Simpson Group has been generally correlated with the St. Peter Sandstone of the Mississippi Valley (Dake, 1921; Suhm and Ethington, 1975).

The Simpson Group consists of five formations, three of which contain basal sandstone members (fig. 9) that are oil-producing reservoirs in the Permian and Anadarko Basins, with the greater production occurring in southern Oklahoma (Jones, 2009). These clean quartz sandstone members are the Connell Sandstone, Waddell Sandstone, and McKee Sandstone Members of the Oil Creek, McLish, and Tulip Creek Formations, respectively (fig. 9) (Suhm and Ethington, 1975; Jones, 2009). These three sandstones are described as containing 95 percent or more quartz, being well-sorted and rounded, and having frosted grains (Howe, 1959; Suhm and Ethington, 1975). They tend to range in thickness from 20 to 50 ft (6 to 15 m) (Jones, 2009).

In west Texas, surface exposures of the Connell Sandstone Member of the Oil Creek Formation occur in the Beach Mountains and the Baylor Mountains in Culberson County (fig. 14), with thicknesses that range from 10 to 30 ft (3 to 9 m), respectively (Suhm and Ethington, 1975). Although the Connell Sandstone Member has properties similar to those of partially age- equivalent midcontinent sandstones of the St. Peter Sandstone (Howe, 1959; Suhm and Ethington, 1975), the Connell in Texas does not appear to be currently mined as frac sand. The Connell Sandstone Member in west Texas is present mostly in the subsurface of the Tobosa Basin, where it was named for a well (W.E. Connell No. 33) that produced oil in Ector County (Schweers, 1949; Wright, 1965; Suhm and Ethington, 1975).

In south-central Oklahoma, the Oil Creek Formation has been recognized in outcrops along the flanks of the Arbuckle Mountains in Murray and Johnston Counties (Buttram, 1913) (fig. 14). The basal sandstone unit of the Oil Creek Formation is mined by U.S. Silica at Mill Creek in Johnston County, Oklahoma, for multipurpose sand used in glass, foundry molds, well stimulation (fracking), and building products sand (U.S. Silica, 2014d).

Deposit Model: Geological Origin and Preservation of Frac Sand Deposits

Provenance and Transport of Lower Paleozoic Midcontinent Quartz Sandstones

Lower Paleozoic multiply-cycled midcontinental sheet sandstones that host frac sand deposits are derived from a complex variety of crystalline basement rock that may include those of the Archean Superior Province; the Paleoproterozic and Mesoproterozoic orogenic Penokean, Yavapai, and Mazatzal Provinces; the Mesoproterozoic midcontinent rift (Runkel and Tipping, 1998); and, in distal regions, the Grenville Province (Konstantinou and others, 2014). Detrital zircon geochronology shows that most zircons in the midcontinent Cambrian and Ordovician quartz arenites were originally sourced from the Grenville orogen (1350–950 Ma) and the Archean Superior Province (2800–2550 Ma), with lesser zircon amounts from the 1500–1350 Ma anorogenic granite-rhyolite suite and the 1950–1600 Ma Paleoproterozoic and Mesoproterozoic orogens (Konstantinou and others, 2014).

The zircon study by Konstantinou and others (2014) provides evidence that indicates that the Cambrian and Ordovician supermature quartz arenites of this region may have been transported from the Archean Huron Basin (2400–2200 Ma) where present-day Lake Huron lies and from the Mesoproterozoic midcontinent rift region (1110–1030 Ma) in present-day northeastern Minnesota. When oriented to the early Paleozoic paleo-equator (Jin and others, 2013), the Huron Basin lies to the east and the midcontinent rift to the northeast of the early Paleozoic marine depositional basin referred to as the Hollandale embayment (Konstantinou and others, 2014).

According to these and other findings, these quartz-rich sands were likely transported by two early Paleozoic river systems for as much as approximately 2,500 km from the Huron Basin through the midcontinent rift before being deposited in the Hollandale embayment to the paleo-west and northwest (Runkel and Steenberg, 2012; Craddock and others, 2013a,b; Jin and others, 2013; Konstantinou and others, 2014). There, they were deposited and continued being reworked by aeolian, wave-dominated delta, and longshore-drift processes in the marine basin (Konstantinou and others, 2014).

Geological Processes Contributing to Frac Sand Formation

The best frac sands are supermature quartz arenites that owe their physical and chemical characteristics to their origin as marine shoreline sands that have a long history of multiple reworking by wind and water (Winfree, 1983), were never deeply buried, or they later underwent diagenesis that reduced or removed cements (Dott and others, 1986; Dott, 2003). Many pure quartz arenites were deposited in non-orogenic basins during Proterozoic and early Paleozoic time (Dott, 2003). The principal processes responsible for the optimal generation of such sands include multi-cycling prior to final deposition and post-depositional intense chemical weathering (Dott, 2003).

Even prior to the deposition of many lower Paleozoic quartz arenites, prolonged chemical weathering of crystalline source rock and of initially derived sediments also occurred (Runkel and Steenberg, 2012). This process removed plagioclase feldspars, which were dominant in the cratonic source area, but were more susceptible to chemical weathering than potassium feldspars that remained (Odom, 1975, 1978).

Principal additional factors contributing to the development of frac sand deposits include multiple cycles of mechanical reworking of sediments that increased mineralogic maturity, and enhanced roundness, sphericity, and sorting of grains (Levson and others, 2012). There are many depositional settings in which sand is reworked, but the geologically older the sand deposit, the more chance it has had to undergo multiple cycles of sediment reworking (Levson and others, 2012). Environments that allow for aeolian abrasion produce exceptional rounding of grains (Dott, 2003). It has been observed that sand in aeolian settings experiences abrasion from wind that can be 100 to 1,000 times more effective at rounding grains than transport by water (Kuenen, 1959; Kuenen, 1960). Additional characteristics of these sands that are consistent with recycling are mixed sources, upward maturation, association with major unconformities, and an inverse relationship between labile (unstable) grain content and grain size (Dott, 2003).

The history and provenance of the source quartz sand affects the strength or hardness of the grains. Quartz grains that have undergone metamorphism or tectonic shear stress may contain weak planes that may fail under the high-pressure conditions to which the sand is exposed during hydrofracking (Zdunczyk, 2007; Levson and others, 2012). Also, single-crystal (monocrystalline) sands have greater compressive strength than do grains consisting of multiple intergrown crystals (polycrystalline) (Levson and others, 2012).

Post-depositional diagenesis can add textural maturation to multi-cycled sands or can independently form pure quartz arenites (Dott, 2003). Long periods of land stabilization are necessary for intense weathering (Dott, 2003). Biological crusts or microbial mats such as marine or lacustrine stromatolites have been suggested as possibly contributing to extended periods of stabilization (Dott, 2003).

Although the best frac sand owes its origin to multicyclical deposition or post-depositional diagenetic processes, mineralogic and texturally mature quartz-rich sands can also form in humid climates through intense single-cycle weathering of underlying crystalline basement rock (Dott, 2003). In stable settings, paleosols form that have undergone chemical etching of quartz grains, dissolution of labile mineral grains, and infilling of pore space with clays (Dott, 2003). Sediments from these paleosols may be fluvially transported and result in the deposition of pure quartz arenites. These quartz arenites, despite their high silica content, do not have well-rounded grains; therefore, they are not ideal for use as frac sands. An example of such deposits is the Carboniferous to Cretaceous Nubian Sandstone that extends from Arabia to northern Africa and Mauritania (Dott, 2003).

Depositional Environments Favoring the Accumulation of Frac Sand

Among the most prospective settings for the accumulation of quartz arenites that source frac sand are marine shoreline and coastal aeolian environments (Mazzullo and Ehrlich, 1983, 1987; Winfree, 1983; Dott and others, 1986; Dott, 2003). As well as marine shoreface environments, marine intertidal and deltaic settings are also considered prospective environments for the generation of frac sand in Canada (Hickin and others, 2010). The perfect example of the ideal combination of frac sand producing environments is the high-quality frac sand of the Ordovician St. Peter Sandstone of the Midwestern United States that formed as coastal aeolian deposits (Mazzullo and Ehrlich, 1983, 1987) and marine offshore and shoreface deposits that were reworked by aeolian processes (Winfree, 1983).

Settings that produce less than ideal sands that may be processed for use as proppant include younger aeolian, glaciodeltaic, and glaciofluvial environments (Hickin and others, 2010). Examples of unconsolidated frac sand from glaciofluvial deltaic and aeolian settings are known from northeastern British Columbia, Canada (Hickin and others, 2010). Also identified as potential unconsolidated sources are Quaternary sand dune deposits derived from older glaciofluvial or sandy glaciolacustrine sediments and (or) sandy bedrock units that have been reworked along major rivers; and deposits of paleobeach ridges and dunes (Levson and others, 2012). In the United States, near Genoa, Nebraska, sand is mined for use as seed sand for resin coating from the highly mature, fluvially deposited, aeolian-reworked, glacial outwash-derived, unconsolidated Holocene Loup River deposits (Epley, 2014).

Post-depositional Processes Affecting Near-Surface Access to Frac Sand

Certain post-depositional processes have enhanced surface access to the targeted frac sand deposits. Fluvial erosion by major river systems has exposed Paleozoic frac sand units to the surface. Examples of this are seen along the course of the Mississippi River from Minnesota to Arkansas. As well, tectonic uplift has enhanced the fluvial exposure of Paleozoic frac sand units in areas bordering the Mississippi River Valley, such as to the east of the Ozark Plateau along the White River in northern Arkansas, where the St. Peter crops out. Complete removal of the units at erosional unconformities has left, at the margins, exposures of truncated layers. Tectonism in the Llano uplift of Texas has prevented deep burial and cementation of the Hickory Sandstone Member and has resulted in the faulted patchwork outcrop pattern that guides the location of “Brown” frac sand mines.

Much of the frac sand mining in the Midwest is from near-surface Paleozoic sandstones of west-central and southwestern Wisconsin and portions of southeastern Minnesota, northeastern Iowa, and northwestern Illinois referred to as the “driftless area” (Syverson and Colgan, 2004). The “driftless area” has long been defined as an area untouched by the advance of the Wisconsinan (pre-35,000 to 10,000 years B.P. [before present]) ice sheets (Syverson and Colgan, 2004; Syverson and others, 2011). As such, the area was neither stripped of the near-surface Paleozoic strata (as in northern Wisconsin) nor deeply buried beneath glacial till (as in eastern Wisconsin). Over the past approximately 2 million years, large volumes of glacial meltwater drained into the Mississippi River system as the Wisconsinan ice sheets receded, deeply eroding and exposing the nearly flat-lying Ordovician and Cambrian strata in the incised terrain (Runkel and Steenberg, 2012; Runkel, 2014). This has resulted in the exposure of the frac sand source units in river bluffs and hillsides and in the near surface.

A combination of downwarping, fluvial erosion, and deposition of glacial sediments has rendered the frac sand source units in the area of southeastern Minnesota west of Olmsted County nearly inaccessible to mining. In this area, subtle downwarping of the Paleozoic beds in the Hollandale embayment (Jirsa and others, 2011), which extends southward into parts of northeastern Iowa (Witzke and others, 2010), resulted in the subsurface preservation of frac sand source units (Runkel and Steenberg, 2012). These Paleozoic units were later fluvially incised during glacial melting and were eventually covered with tens to hundreds of feet of unconsolidated glacially derived sediments (Mossler and Book, 1984), making access to the frac sand units unfeasible in that area (Runkel and Steenberg, 2012). To the west, however, in the valley of the Minnesota River, frac sand units are exposed along the river banks (Runkel and Steenberg, 2012; Runkel, 2014).

Post-glacial depositional processes have influenced the distribution and thickness of overburden on the frac sand source units of the Midwest. Although the glacial-outwash drainage system in the driftless area cut deeply into the Ordovician and Cambrian beds of western Wisconsin and extreme eastern Minnesota, removing major thicknesses of overburden from most of the frac sand mining area, relict glacial-outwash deposits obscure frac sand source units in some of the river valleys (Runkel and Steenberg, 2012). Quaternary loess deposits also form several meters of cover on upland divides in the driftless area of western Wisconsin (Syverson and others, 2011). Mining of the frac sand units, even in the driftless area, may not be locally feasible because of these types of overburden deposits (Runkel and Steenberg, 2012).

Post-depositional Processes Affecting the Quality of a Potential Frac Sand Source

In situ post-depositional processes can alter the sphericity and roundness of clastic grains and modify friability by the addition or removal of cementing agents. Such alterations are common in buried consolidated sandstones and have influenced the suitability of many deposits as frac sand sources.

Despite the overall desirability of St. Peter Sandstone as a frac sand source, there are local areas in which portions of the unit naturally exhibit characteristics that are less optimal for use as frac sand. In these areas, portions of the deposit have undergone diagenetic alteration that has resulted in secondary grain overgrowths, dissolution, and cementation of the sand (Winfree, 1983; Kelly, 2006; and Kelly and others, 2007). For example, quartz arenites of the St. Peter Sandstone in an area of southwestern Wisconsin and southeastern Minnesota, where they have a shallow (<1 km) burial history, show authigenic quartz overgrowths on detrital quartz grains (Kelly, 2006; Kelly and others, 2007). These overgrowths are interpreted to have originated during the formation of silcretes by precipitation from meteoric water during paleofluid flow events early in the St. Peter Sandstone's history (Kelly, 2006; Kelly and others, 2007). Quartz grain overgrowths were also observed in the St. Peter Sandstone in south-central Wisconsin (Clayton and Attig, 1990). These grain overgrowths reduce roundness and sphericity and introduce weaker planes along authigenic crystal boundaries. The precipitation of silica cement occludes porosity and reduces friability.

A different series of diagenetic processes altered original porosity and friability of the quartz arenite of the Jordan Formation in Allamakee County of northeastern Iowa, which resulted in calcitic sandstone nodules with hematitic rims and calcite-cemented layers (Johnson and Swett, 1974). Formation of the nodules and cemented layers is attributed to fluctuations in temperature, groundwater table, and proximity to organic-rich soil horizons that might have influenced Eh, pH, or Fe ion concentration. The diagenetic sequence that formed the nodules began with the partial and selective calcite cementation of the sandstone by the precipitation of large (> 5 mm) euhedral or subhedral calcite crystals that incorporated the quartz sand grains, which are often referred to as sand crystals or sand-calcite crystals (Johnson and Swett, 1974). This was followed by selective dissolution of the outer boundaries of the large calcite sand crystals, which resulted in reshaping the sand crystals into subspherical and irregular nodular forms (Johnson and Swett, 1974). Next came the introduction of hematitic shells at the rim of the nodules, then calcite dissolution continued to shape the nodules near the soil horizon, and hematite precipitation continued within previously formed hematite shells of the nodules (Johnson and Swett, 1974). Furthermore, remobilization of calcite from the nodular layers may have resulted in the calcite-cemented beds (Johnson and Swett, 1974).

In other post-depositional settings, sandstones that were originally cemented with carbonate minerals can develop increased friability as a consequence of cement dissolution during early diagenesis or to later stage post-depositional exposure to groundwater flow or surface weathering.

Sequence Stratigraphic Perspectives on Sheet Sands that Source Frac Sand

The lower Paleozoic supermature quartz arenites of central North America owe their mineralogic and textural maturity to strong chemical weathering of the source terrane in a warm, wet climate and to a protracted history of transport and reworking (Sloss, 1988). Their sedimentary and stratigraphic character is influenced by relatively slow rates of basin subsidence and low epicratonic relief (nearly flat regional shelf gradient), with a base level of sedimentation at or very near sea level (shallow bathymetry) (Sloss, 1988; Runkel and others, 2007). These Middle and Upper Cambrian to Lower Ordovician sands were deposited on a broad, shallow shelf on the relatively stable interior of the North American central craton (Runkel and others, 2007) during the Sauk and Tippecanoe sequences of Sloss (1963). Efforts to apply sequence stratigraphic architecture based on models from foreland basins or other rapidly subsiding areas have been frustrated by the lithologic and textural homogeneity that obscures facies and by the thin, yet widespread distribution of these slowly deposited continental interior sands (Runkel and others, 1998; Runkel and others, 2007). Despite this, a finely detailed comparison of the sequences and parasequences of the upper Mississippi Valley lower Paleozoic epeiric ramp sheet sands with those of the Cretaceous Interior Seaway reveals that the stratal elements are fundamentally the same (Smith and others, 1993; Nadon and others, 2000; Runkel and others, 2007).

The St. Peter Sandstone is a diachronous (time-transgressive) deposit that extends from the subsurface of the Michigan and Illinois Basins westward to the outcrops on the Wisconsin arch (Barnes and others, 1996). The formation's stratigraphic nature is the product of the subtle interplay between basin subsidence and eustatic sea level fluctuations on a relatively stable craton (Barnes and others, 1996). Because of very different depositional bathymetries and resultant facies patterns, it is difficult to correlate the St. Peter Sandstone stratigraphy of the upper Mississippi Valley with that of the Michigan Basin (Barnes and others, 1996). Despite this, similar sequence stratigraphic systems tracts are recognized in both the deep basins and on the low-relief cratonic shelf (Barnes and others, 1996).

In the upper Mississippi Valley, the St. Peter Sandstone is described as a classic marine transgressive blanket or sheet sand (Dapples, 1955) that is typically widespread and thin, 30 to 40 m (98 to 131 ft) thick (Mai and Dott, 1985), and laid down on the regionally extensive sub-Tippecanoe unconformity (Barnes and others, 1996). The base of the unit was deposited in fluvial and aeolian settings followed up-section by the more common shallow marine deposits that include a complex facies mosaic of shoreface, sublittoral sheet sands, and barrier-island deposits (Witzke, 1980; Mazzulo and Ehrlich, 1983, 1987; Mai and Dott, 1985; Dott and others, 1986).

In contrast, deposition of the St. Peter Sandstone in the slowly, but persistently, subsiding Michigan Basin was accompanied by increased accommodation space, along with a ready sediment supply from the north, resulting in a higher sedimentation rate and a maximum thickness in the basin center of 366 m (1,200 ft) compared to the thinner deposits on the broad interior shelf (Barnes and others, 1996). The St. Peter Sandstone in the Michigan Basin is interpreted as a shallow marine paralic and shelf deposit laid down on the unconformable surface of the regressive informal Brazos shale of the Upper Prairie du Chien Group during the early stages of the Tippecanoe transgression (Barnes and others, 1996). Overlying the St. Peter Sandstone, the Glenwood Formation is a condensed section succeeded by highstand deposits of the Black River Limestone (Barnes and others, 1996). The higher depositional rate and the presence of carbonates within the St. Peter of the Michigan Basin allow for detailed electric log distinctions of lithofacies in the subsurface. Using log responses from a combination of gamma-ray logs and density and neutron porosity logs to distinguish electrofacies, a high-resolution sequence stratigraphic model for the St. Peter Sandstone and the Glenwood Formation was proposed by Nadon and others (2000). The typical transgressive-regressive sequence stratigraphic architecture was observed in the southeastern portion of the basin where transgressive and highstand carbonates overlie clean sands of the lowstand systems tract and laterally interfinger with interbedded carbonates and siliclastics of the transgressive and highstand systems tracts (Nadon and others, 2000). These systems tracts are less defined in the northwestern portion of the basin, being proximal to the sand source area, as thick deposits of clean sandstones of lowstand and highstand tracts are rarely interrupted by the more distal silty, shaley, or carbonate facies (Nadon and others, 2000).

Although the sequence stratigraphic model of Nadon and others (2000) may lend new insights for the continued development of the St. Peter Sandstone as a petroleum reservoir within the Michigan and Illinois Basins, it may have only limited application in the exploration for near-surface occurrences of sheet sands that could be a source for frac sand.

Alternative Proppants

Substitutes for natural frac sand include resin-coated sand and manufactured proppants such as ceramic beads made from materials obtained from sintered bauxite (Beckwith, 2011; Dolley, 2012) or small metal beads made from aluminum (Geology, 2013).

Resin-Coated Sand

Proppants manufactured as resin-coated sand are touted as being better performing than "Northern White" sand as to permeability, conductivity, crush resistance, and reduced flowback in a variety of temperature and pressure conditions (Preferred Sands, 2012). The compressive strength (crush resistance) of the grains is increased by the resin coating, which shields the grains from fracture closure stresses, prevents shattering, and contains any fines produced (Pallanich, 2013; Santrol, 2014). Another advantage of resin-coated proppants is that they can be made available in a range of mesh sizes (Preferred Sands, 2012). Resin-coated sands consist of less-optimal silica sand (as a seed or substrate) that has been coated with either phenolic or non-phenolic resin to reach the desired shape, grain size, and other properties. According to a manufacturer of proppants using non-phenolic resin, these proppants are environmentally "greener" because they require less energy to produce, and they are more cost-effective than the phenolic resin-coated proppants (Preferred Sands, 2012).

Resin coatings can be either pre-cured (bonded to grains before going downhole) or curable (bonds grains together in response to high downhole pressures and temperatures) to minimize or prevent proppant flow-back (Beckwith, 2011; Pallanich, 2013). Curable resin treatments can be applied to both sand and ceramic proppant (Beckwith, 2011).

Synthetic Proppants

Ceramic proppants are manufactured from nonmetallurgical bauxite or kaolin clay that is sintered (powdered and baked in high-temperature kilns) to reduce water content and increase density, roundness, and strength (Beckwith, 2011). In this process, the sintered bauxite is mixed with additives such as aluminum oxide, silicate, and iron-titanium oxide (ShanXi GuangYu Ceramic Proppants, 2012). Despite their higher cost compared to natural frac sand, ceramic proppants are more homogenous in composition and more uniform in size and roundness, giving them a higher fracturing strength in wells at greater depths and higher pressures, and they have greater conductivity than either natural frac sand or resin-coated proppants (ShanXi GuangYu Ceramic Proppants, 2012). An additional advantage of synthetic proppants is that their specific gravity and grain size can be matched to the viscosity of the fracking fluid and to the anticipated size of fractures in the rock to develop from the fracking treatment (Geology, 2013).

The manufacture of ceramic and aluminum metal bead proppants relies upon natural resources of aluminum-rich minerals that include bauxite, kaolinite, alunite, and halloysite (Rupke, 2014). Because the production of alumina on a commercial scale in the United States relies almost entirely on its recovery from bauxite (Bray, 2014), the synthetic proppant industry is dependent upon the domestic and global supply of bauxite.

Nearly all of the bauxite consumed in the United States is imported, and there is no government stockpile (Bray, 2014). The world bauxite resources are estimated at 55 to 75 billion tons and are distributed on the following continents: Africa (32 percent), Oceania (23 percent), South America and the Caribbean (21 percent), Asia (18 percent), and elsewhere (6 percent) (Bray, 2014). The principal countries from which the United States imports both bauxite and alumina are Jamaica, Brazil, Guinea, and Australia (Bray, 2014). Additional countries that mine bauxite are China and India (Beckwith, 2011).

Potential non-bauxite sources for alumina in the United States might include clay, alunite, and anorthosite (Bray, 2014). Kaolin (an aluminum silicate clay mineral) deposits in central Georgia are the principal U.S. sources of kaolin (Schroeder, 2014). CARBO, a ceramic proppant producer, has a facility in Toomsboro, Georgia, that is close to these kaolin sources (Beckwith, 2011). Globally, countries with substantial resources of kaolin include Brazil, Bulgaria, France, the United Kingdom, Iran, Germany, India, Australia, (North and South) Korea, China, and the Czech Republic (Beckwith, 2011).

As the synthetic proppant industry grows with advancements in technology, the suitability of alternative raw materials such as coal wastes and oil shales is being explored (Bray, 2014). One example of success in this effort is credited to an engineered proppant developer at The Pennsylvania State University (Penn State), referred to as Nittany Extraction Technologies Company (NETCo), whereby it is using waste material that includes glass, alumina silicate mine tailings, fly ash, metallurgical slags, and rock cuttings from oil and gas drilling as raw materials in the manufacture of its ceramic proppant (Beckwith, 2011).

Resin-Coated Proppant Substrate Sand Source Units in the United States

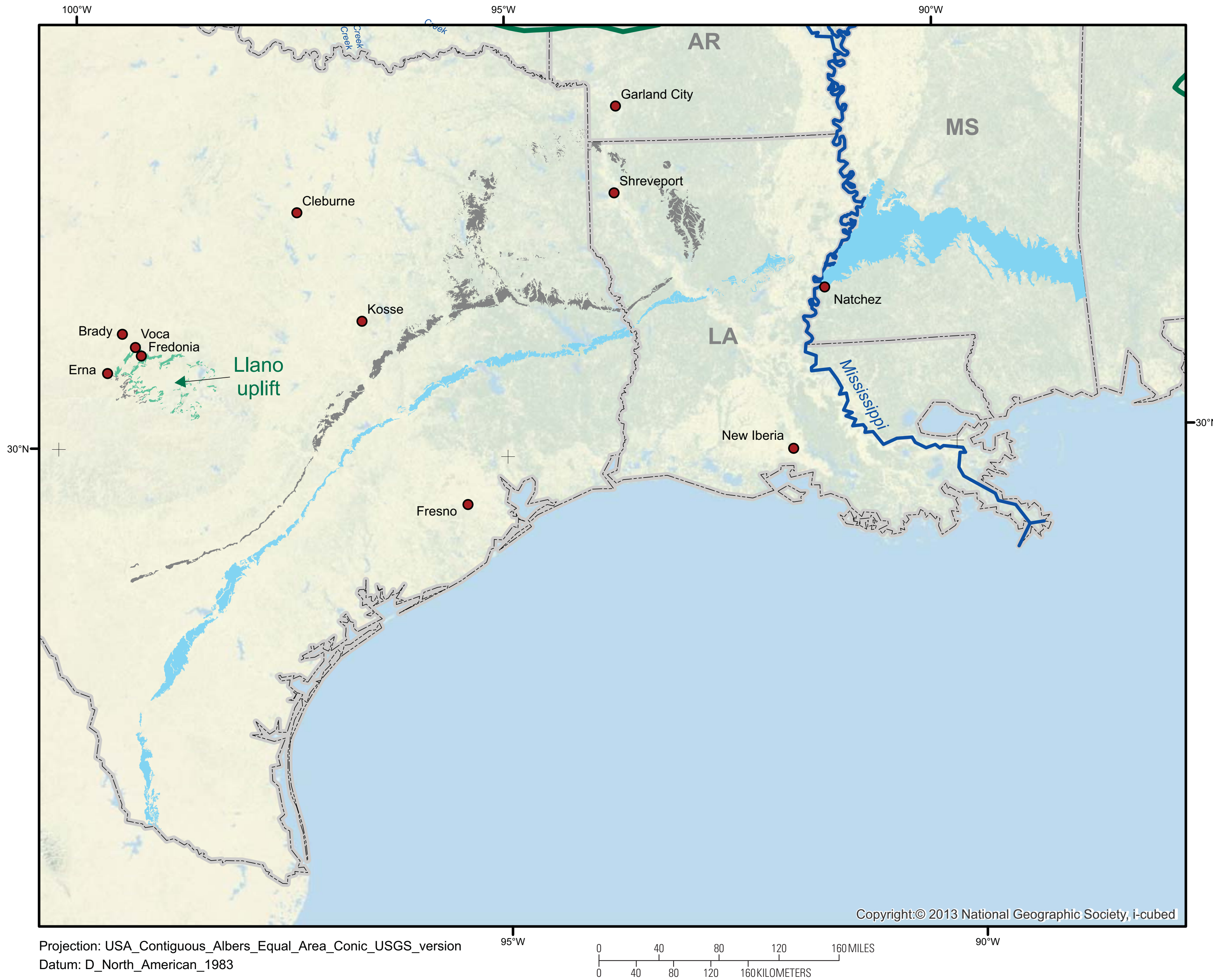
Sparta Sand

The Eocene Sparta Sand, a formation within the Claiborne Group, occurs in the northern Gulf Coast States (fig. 15, pl. 1). In east Texas, it is described as a very fine- to fine-grained quartz sand that contains silty clay partings; is locally carbonaceous, laminated, very pale orange to grayish brown, about 200 ft (61 m) thick; and weathers yellowish brown to reddish brown (Barnes, 1970). Because of its proximity to the Haynesville-Bossier and other shale gas plays, the Sparta Sand was evaluated for its potential as frac sand. The Louisiana Geological Survey determined that two samples of the Sparta Sand collected from an area in eastern Louisiana were marginally acceptable for use as proppant on the basis of sphericity, acid solubility, bulk density, and a crush resistance of 7,000 psi (Durham, 2014; Milner and John, 2014). Resin coating would more than double its crush resistance, enhancing its effectiveness in the deep Louisiana plays (Durham, 2014; Milner and John, 2014). The Sparta is being considered for use in the manufacture of resin-coated sand at Unimin's operation near Sibley, Louisiana (northeast of Shreveport) (Milner and John, 2014).

Catahoula Formation

The Oligocene and Miocene Catahoula Formation occurs in the northern Gulf Coast States (fig. 15, pl. 1). In outcrops in Mississippi, the Catahoula consists of as much as 600 ft (183 m) of nonmarine to marginal marine (fluvial to deltaic?), partly carbonaceous and varicolored gravel, sand, silt, and clay (Tew, 1992). The Louisiana Geological

Figure 15. Surface exposures of Tertiary sand source units in the Gulf coastal region that are used or are being considered for use as lower-quality frac sand or in the manufacture of resin-coated sand. These include the Eocene Sparta Sand (dark gray) and the Oligocene and Miocene Catahoula Formation (light blue). Also shown is the previously discussed Hickory Sandstone Member (light green) of the Riley Formation in the Llano uplift area of central Texas. (Red dots are towns for reference.)—Following page



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Survey determined that two samples of sand from the Catahoula Formation collected from an area in east-central Louisiana were marginally acceptable for use as proppant on the basis of sphericity, acid solubility, bulk density, and a crush resistance of 7,000 psi (Durham, 2014; Milner and John, 2014). Resin coating would more than double its crush resistance, enhancing its effectiveness in the deep Louisiana plays (Durham, 2014; Milner and John, 2014). According to Durham, Milner speculated that Catahoula being mined near Natchez, Mississippi, might be used in resin-coated proppant manufacture (Durham, 2014).

Bidahochi Formation

The nonmarine Pliocene Bidahochi Formation extends from northeastern Arizona (fig. 16, pl. 1) into nearby parts of New Mexico in the area northeast of the Little Colorado River (Repenning and Irwin, 1954).

The sediments of the Bidahochi Formation were deposited by southwestward-flowing streams (Hack, 1942) and were derived from the Chuska Mountains and from the Defiance, Zuni, and Mogollon Plateaus (Kiersch and Keller, 1955). The uppermost informal member of the Bidahochi Formation is a tuffaceous, fluvio-lacustrine sandstone that is composed predominantly of white to very pale brown, cross-bedded, poorly cemented, medium- to fine-grained, argillaceous sandstone with a few beds of white rhyolitic ash (Repenning and Irwin, 1954). This sandstone unit has a maximum thickness of approximately 600 ft (183 m) near Greasewood, Arizona (Kiersch and Keller, 1955). It is an immature sandstone that has been used as frac sand only sparingly and in shallow wells (Zdunczyk, 2007). In 2012, it was announced that Preferred Sands purchased a sand mining operation with as many as three quarries in the Sanders, Arizona, area and is producing resin-coated proppants (Arizona Geology, 2012).

Loup River Sand

Quaternary fluvial deposits along the Loup River near Genoa, Nebraska (fig. 17, pl. 1), are aeolian reworked sands derived from Pleistocene glacial outwash (Epley, 2014). These are being mined and processed by Preferred Sands of Genoa, Nebraska, for resin-coated sand proppant (Shale Reporter, 2013). These sands are not featured as a mapped unit in this report.

Potential Additional Frac Sand or Proppant Substrate Sand Sources in the United States

Additional known silica sand sources have been examined by several investigators for their potential future use in the proppant industry. The published results of these studies range widely from a few subjective remarks to a full characterization of the samples analyzed. In all cases, however, the determination of frac sand suitability of any specific rock unit described here is restricted to the referenced location or sampled site, and therefore does not necessarily apply to the full mapped extent of the host unit as shown on the accompanying maps in the figures and plate. Note that lithologic character varies widely across broad areas that are mapped as potential frac sand host units; therefore, these mapped units are featured merely as guides for future study.

Although the units discussed here contain pure silica sands (quartz arenites), many of which have been mined for use in glass manufacturing, none meets all the additional specifications for ideal frac sand under the API guidelines (Zdunczyk, 2007, 2014; Maslowski, 2012; Rupke and Boden, 2013; Wolfe, 2013; Marshall and others, 2014; Rupke, 2014; Rupke and Boden, 2014). Most of these units, therefore, are rated as having low to medium suitability for frac sand under current API standards, but, in practice, sand used as frac sand is not always ideal. Despite its relative lower quality or finer grain-size range, a portion of the sand mined from traditional silica mines in these source units is sold and used as frac sand in some shale gas plays, especially in shallower wells (Zdunczyk, 2014). Additionally, some of the units discussed here may be suitable for future use in the manufacture of resin-coated proppant. Not described in this report are the Lower Cretaceous Paluxy and Trinity Sands in Texas and other sands in Arkansas that are mentioned in name only by Zdunczyk (2014). The potential frac sand or proppant substrate sand source units reviewed here are discussed by region: Appalachian, Great Plains, and southwestern.

Figure 16. Surface exposures of the Bidahochi Formation in northeastern Arizona that is used as lower-quality frac sand or used in the manufacture of resin-coated proppant. The Bidahochi Formation is shown in orange. (Red dots are towns referenced in the text.)—Following page

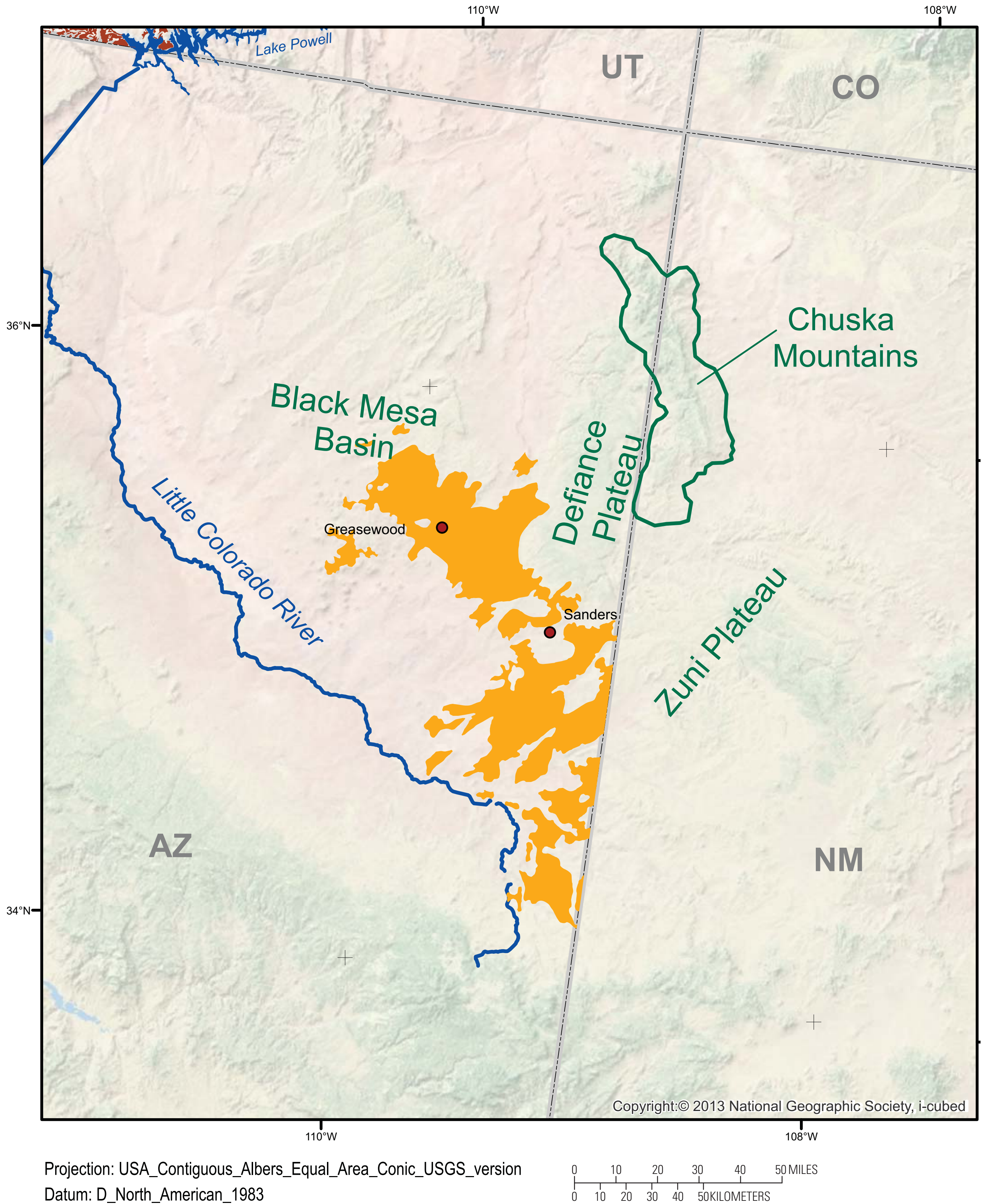

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Figure 17. Surface exposures of modern fluvial sand deposits along the Loup River near Genoa, Nebraska, that are being dredge mined from the Loup River Canal for use as resin-coated sand. (The town of Genoa appears as a red dot.)

Appalachian Region

Antietam Formation

The Lower Cambrian Antietam Formation (also, Erwin Formation according to Sweet, 1986) is the uppermost formation within the Chilhowee Group in Pennsylvania (Hack, 1982; Ryder and others, 1992) (fig. 18, pl. 1). Sandstone of the Antietam Formation has roundness and sphericity of nearly 6.0; however, because it could not meet the test for crush resistance, it is not considered a good potential source for frac sand (Zdunczyk, 2007).

Chickies Formation

The Lower Cambrian Chickies (also, "Chiques") Formation (also, Quartzite) is exposed at Chickies Rock on the Susquehanna River in Lancaster County, Pennsylvania (Walcott, 1896) (fig. 18, pl. 1). Although subsequently metamorphosed, the Chickies Formation is an example of the widespread marine Cambrian and Ordovician quartz arenites derived from the North American Craton or Canadian Shield (Pettijohn and others, 1972) that were deposited as basal sands on the eroded Proterozoic surface (Walcott, 1896). The Chickies Quartzite is mined for silica sand (Zdunczyk, 2007).

Clinch and Tuscarora Sandstones

The Clinch Sandstone is a mature quartz arenite or orthoquartzite of Early Silurian age (also "Clinch Mountain Sandstone") that is recognized in northeastern Tennessee (Driese, 1988), eastern Kentucky (Englund and others, 1963), and southwestern Virginia (Miller and Fuller, 1947) (fig. 18, pl. 1). According to Herron (2006), the Clinch Sandstone of Tennessee, Kentucky, and Virginia is stratigraphically equivalent to the Tuscarora Sandstone of the northern Appalachian Basin. The Upper Ordovician to Lower Silurian Tuscarora Sandstone (also, Quartzite) is the uppermost formation within the Judy Gap Group in West Virginia (Chen, 1977) and occurs elsewhere in the Valley and Ridge Province of Pennsylvania, Maryland, and Virginia (Faill and others, 1989). The Tuscarora is described as light-gray to light-brown, fine- to medium-grained, medium- to thick-bedded quartzite that weathers to white (Faill and others, 1989).

Within the Clinch Mountain system of northeastern Tennessee, the Clinch Sandstone is being mined for silica sand by Short Mountain Silica at Short Mountain in Hawkins County (Zdunczyk, 1992; Short Mountain Silica, 2014). Although the Clinch Sandstone generally does not meet the criteria for frac sand (Zdunczyk, 2007), the Short Mountain Silica Company states that a frac sand facility was installed at the Short Mountain location in 2012, where it produces 30/50 and 40/70 mesh sand used in the oil and gas industry (Short Mountain Silica, 2014).

Oriskany Sandstone/Group

The U.S. Geological Survey recognizes the use of the name Oriskany as both a group and a formation of middle Early Devonian age in the Appalachian region. The Oriskany Group includes the Esopus Formation at the top and the Port Ewen Formation at the base, and where the undifferentiated deposits of Oriskany age are chiefly or wholly sandstone, the term Oriskany Sandstone is applied (Wilmarth, 1938). In central Pennsylvania, western Maryland, northern West Virginia, and parts of Virginia, the Oriskany Group is divided into the Ridgeley Sandstone (upper) and Shriver Chert (lower) (Wilmarth, 1938) (fig. 18, pl. 1). Oriskany Group is mapped in Sussex County, northwestern New Jersey, where it is subdivided into the Ridgeley Sandstone (upper), Shriver Chert (middle), and Glenerie Formation (lower) (Monteverde, 1992).

The Ridgeley Sandstone in west-northwest Virginia is as much as 300 ft (91 m) thick and is high in silica, predominantly white to light tan to light gray, and in places has a calcareous matrix that has been leached along fractures causing the rock to become friable sandstone or loose sand, making it especially attractive as a potential source of frac sand (Sweet, 1986). Unimin Corporation near Gore, Frederick County, Virginia, quarries the Ridgeley (Oriskany) Sandstone for glass sand (Sweet, 1986).

Elsewhere in Virginia, the high-silica sandstone formation, referred to as the Oriskany Sandstone, has been described by Scholle (1979) as having quartz grains that are well-rounded and show no euhedral overgrowths; however, they have irregular line contacts with adjacent minerals, and many quartz grains have strain shadows and Boehm lamellae suggesting significant deformation that would compromise their capacity to withstand high crush pressures (Scholle, 1979).

For the past century, U.S. Silica has been mining the 99.9 percent pure silica sand of the Devonian Oriskany Sandstone along the Warm Springs Ridge in northeastern West Virginia for use in non-proppant industries (U.S. Silica, 2014a).

Sylvania Sandstone

The Middle Devonian Sylvania Sandstone is the lowermost formation within the Detroit River Group. It is exposed in northwestern Ohio (fig. 18, pl. 1) where it unconformably overlies rocks of the Silurian Salina Group (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]; Wolfe, 2013). The Sylvania Sandstone ranges in thickness from 0 to 95 ft (0 to 29 m) and is described as a white, friable sandstone with well-rounded quartz grains; may contain scattered masses of calcite, celestite, and dolomite; and is interbedded with arenaceous dolomite with bands of chert (Wolfe, 2013). The sandstone is exposed in a quarry in Lucas County, Ohio, where it was historically used in the Toledo glass industry, and on the south bank of the Maumee River in Wood County (Heinrich, 2001). Wolfe (2013) names the Sylvania Sandstone among potential future sources for frac sand in Ohio.

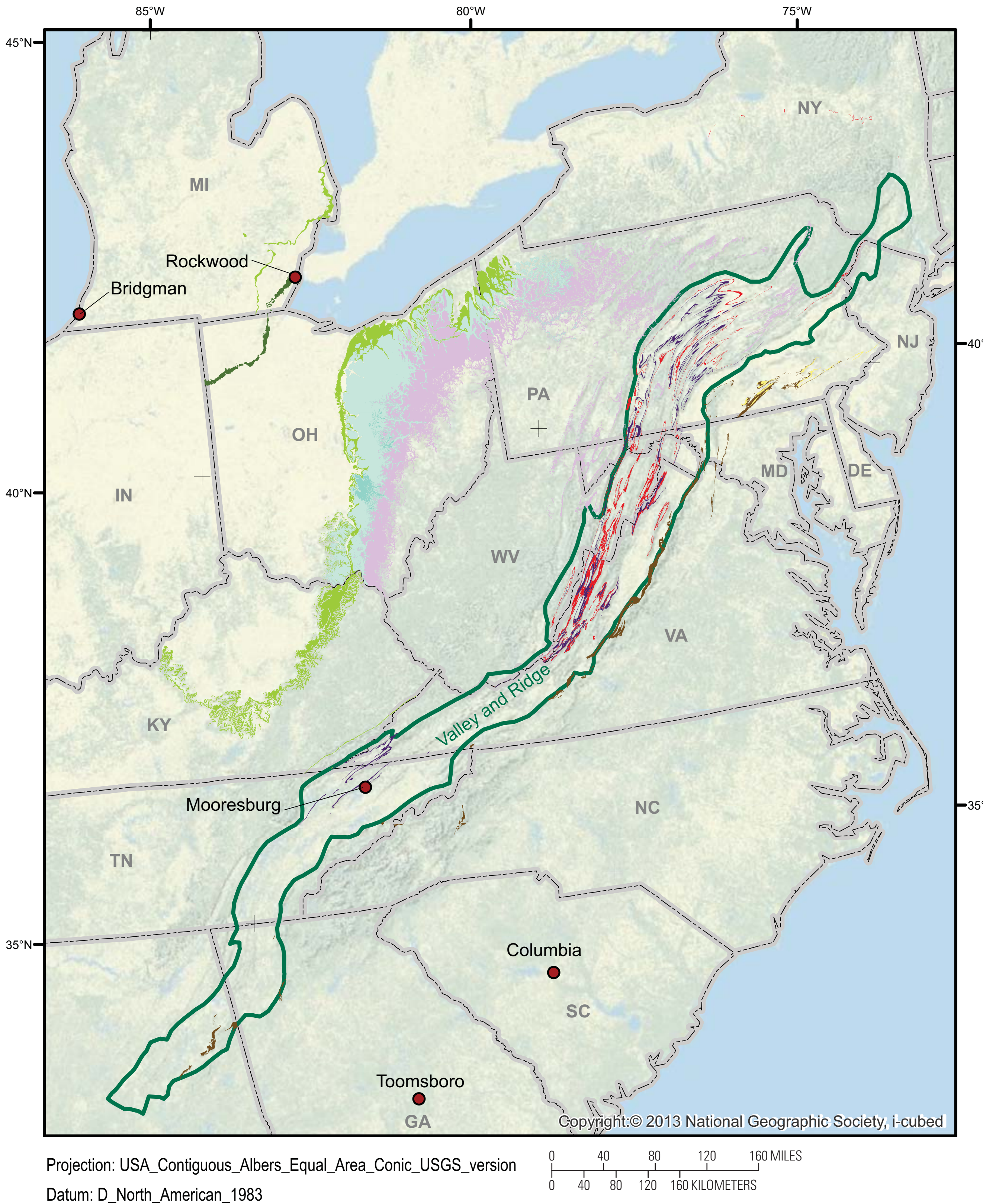


Figure 18. Surface exposures of quartzose sand source units in the Appalachian region that have limited potential suitability for use as frac sand. The units are identified as mapped from east to west as the Antietam (dark brown) and Chickies (yellow) Formations, Oriskany (bright red) and Clinch/Tuscarora (dark blue) Sandstones, Pottsville (lavender) Group, Buena Vista and Black Hand Sandstone Members (pale turquoise) of the Cuyahoga Formation, Black Hand Sandstone Member (medium turquoise), and Berea (light green) and Sylvania (deep green) Sandstones. (Towns appear as red dots.)

The Sylvania Sandstone extends into Michigan, where it has characteristics typical of aeolian reworked marine sands that were likely sourced during Devonian time from outcrops of the Ordovician St. Peter Sandstone (Sherzer and Grabau, 1910). The Sylvania Sandstone is mapped in the subsurface of the Michigan Basin where its thickness increases northwestward reaching a maximum of nearly 400 ft (122 m) (Heinrich, 2001). The unit has been mined for glass sand in Rockwood, Wayne County, southeastern Michigan, by the Ottawa Silica Company (Heinrich, 2001). U.S. Silica mines this unit at Rockwood for use in non-proppant industries (U.S. Silica, 2014f).

Berea Sandstone

In Ohio, the Upper Devonian Berea Sandstone (fig. 18, pl. 1) is overlain by the Lower Mississippian Sunbury Shale (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]). The Berea Sandstone is light brown, medium to coarse grained with subrounded quartz grains, with a silica content of generally greater than 91 percent, aluminum oxide about 4 percent, and iron oxide less than 1 percent (Wolfe, 2013).

Buena Vista Sandstone Member

The Lower Mississippian Buena Vista Sandstone Member of the Cuyahoga Formation (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]) (fig. 18, pl. 1) is a thin-bedded, fine- to medium-grained, subrounded quartz sandstone that is exposed in south-central Ohio and has been historically mined as a building stone (Wolfe, 2013).

Black Hand Sandstone Member

The Lower Mississippian Black Hand Sandstone Member of the Cuyahoga Formation (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]) (fig. 18, pl. 1) contains silty and conglomeratic facies; however, it also occurs as a massive, coarse-grained, 98-percent silica sandstone as much as 100 ft (31 m) thick that is mined as frac sand, as well as industrial sand in Knox County, Ohio (Wolfe, 2013).

Sharon Sandstone

The Pennsylvanian Sharon sandstone is the basal informal unit of the Pottsville Group in Ohio, where it unconformably overlies Mississippian strata (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]; Wolfe, 2013) (fig. 18, pl. 1). Elsewhere, in Pennsylvania, Maryland, and other parts of Ohio, the unit is recognized as the Sharon Conglomerate Member of the Pottsville Formation (Rice and others, 1994). The Sharon Conglomerate Member crops out in Pennsylvania and northeastern Ohio (Fuller, 1955) and is described as a massive, fine- to coarse-grained, high-silica sandstone and pebble conglomerate, with a thickness range from 10 to 60 ft (3 to 18 m) as exposed in quarries (Wolfe, 2013). In Ohio, the Sharon sandstone is mined for glass, industrial, and frac sand uses (Wolfe, 2013). Parameters that qualify the Sharon sandstone for use as a frac sand include silica content that can exceed 99 percent, roundness/sphericity of 0.6–0.7, solubility of 2.9 percent, turbidity of 19, crush resistance of as much as 6,000 psi, and an acceptable size distribution (Wolfe, 2013). The unusually high silica content of this unit is attributed by Fuller (1955) to the multi-cycling and transport of sediments long-removed from the older igneous, metamorphic, and sedimentary source rock by streams of considerable competency and eventually deposited as a delta in a shallow basin overlying the Mississippian unconformity.

The Sharon sandstone is mapped with many other units within the Pottsville Group and is, therefore, overrepresented on figure 18 and plate 1.

Massillon Sandstone

The Pennsylvanian Massillon sandstone is an informal unit within the Pottsville Group in Ohio (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]; Wolfe, 2013) (fig. 18, pl. 1). The unit is described as a light-brown to white, fine- to medium-grained, high-silica sandstone with a maximum thickness of 100 ft (31 m) in east-central and northeastern Ohio. Although currently mined for industrial sand and building stone, it may be considered by some for future use in fracking because of its roundness/sphericity of 0.5–0.6, acid solubility of 1.9 percent, and turbidity of 78 NTU (Wolfe, 2013).

Great Plains Region

Deadwood Formation

The Upper Cambrian and Lower Ordovician Deadwood Formation in South Dakota (fig. 19, pl. 1) has been described as a variegated, yellow to red, brown, gray, and green, glauconitic, conglomerate, sandstone, shale, dolomitic limestone, and dolomite, with a thickness of 4–400 ft (1–122 m) (Martin and others, 2004). Although studies by Ching (1973) and Huq (1983) indicated that parts of the Deadwood Formation are potential sources for frac sand, the South Dakota Geological Survey reports that the formation is not a prospective frac sand source (Marshall and others, 2014). When compared with API requirements for frac sand, the Deadwood Formation does not consist of >99 percent quartz, has too broad a grain-size distribution, has grains that are not the correct shape, or is tightly cemented (Rapid City Journal, 2014). Despite these differences in assessments of the Deadwood Formation's frac sand potential, South Dakota Proppants, LLC, is currently pursuing permits to develop a mine, processing plant, and transportation hub in an area of the Black Hills National Forest (Hirji, 2014).

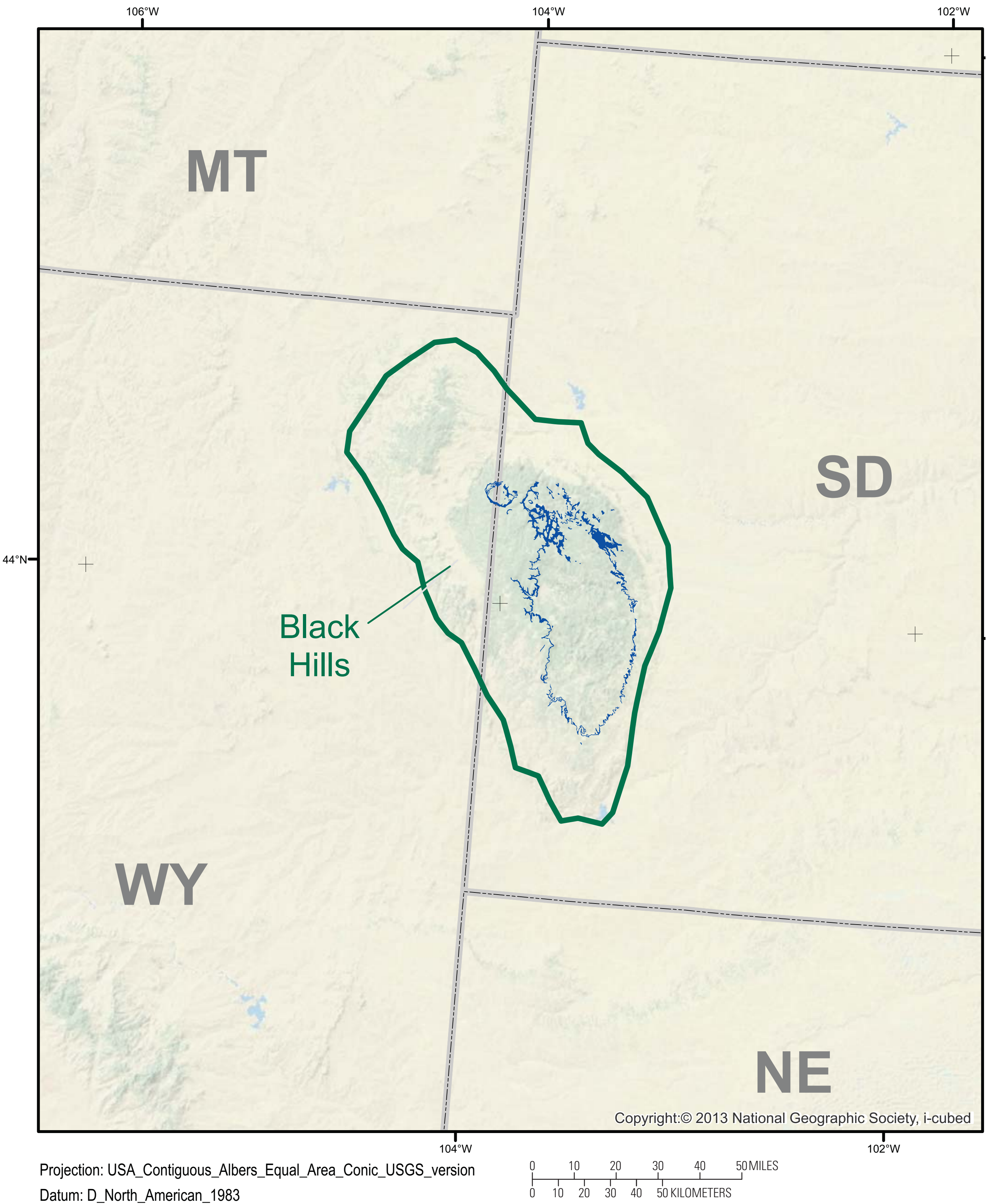


Figure 19. The Cambrian and (locally) Lower Ordovician Deadwood Formation (dark blue) along the flanks of the Black Hills of South Dakota in the Great Plains Region is reported to be a potential frac sand source.

Southwestern Region

The southwestern region, consisting mostly of Utah, Arizona, Colorado, and New Mexico contains thick and widespread deposits of Mesozoic quartz arenites with subrounded to well-rounded grains formed from multiple reworking of sand in aeolian and marine shoreface settings. Several of these units, along with Quaternary aeolian dune sands, have been the focus of published studies evaluating their suitability as frac sand.

White Rim and Cedar Mesa Sandstone Members

The Lower Permian White Rim and Cedar Mesa Sandstone Members of the Cutler Formation are recognized in the Paradox Basin of Utah (Baker and Reeside, 1929; Steele, 1987). The White Rim Sandstone Member is a quartz sandstone of shallow-margin origin that forms the top of the Cutler Formation and is overlain by the Triassic Moenkopi Formation (Blakey, 1974). It was deposited in a coastal environment during marine transgression where it was later exposed to aeolian and other nonmarine processes (Steele, 1987). Where the White Rim Sandstone Member and the Cedar Mesa Sandstone Member are exposed in Emery County, Utah (fig. 20, pl. 1), they are proposed as high-potential frac sand sources (Rupke and Boden, 2013; Rupke, 2014; Rupke and Boden, 2014). Samples of these units showed a relatively fine size distribution with the potential to provide a 30/50- or 40/70-sized product, at least a 97-percent silica content, and marginal roundness when compared to the ideal frac sand sources; yet, more testing such as crush resistance is needed to determine the true degree of suitability as a frac sand (Rupke and Boden, 2013; Rupke, 2014; Rupke and Boden, 2014).

Wingate Sandstone

The Lower Jurassic Wingate Sandstone (Dubiel, 1989) is within the Glen Canyon Group of Arizona, Colorado, New Mexico, and Utah (Peterson and Pipiringos, 1979) (fig. 20). Harshbarger and others (1957) subdivided the formation into two members (in descending order): the Lukachukai Member, and the Rock Point Member. The Lukachukai Member is a reddish-brown, fine- to very fine-grained, cross-bedded, cliff-forming, quartz sandstone with a thickness of 300 ft (91 m); and the Rock Point Member is a reddish-orange parallel-bedded, thin bedded siltstone and subrounded to subangular quartz sandstone with a thickness of 344 ft (105 m) (Harshbarger and others, 1957). The Lukachukai Member is widespread, occurring extensively throughout the Colorado Plateau; whereas, the Rock Point Member is mainly restricted to northeastern Arizona and northwestern New Mexico (Harshbarger and others, 1957). Dubiel (1989) removed the Rock Point Member from the Wingate Sandstone of the Glen Canyon Group and reassigned it to the Upper Triassic Chinle Formation. As a result, the designation "Lukachukai Member of the Wingate" was abandoned, and the sandstone formerly assigned to the Lukachukai was assigned to the greater Wingate Sandstone (Dubiel, 1989).

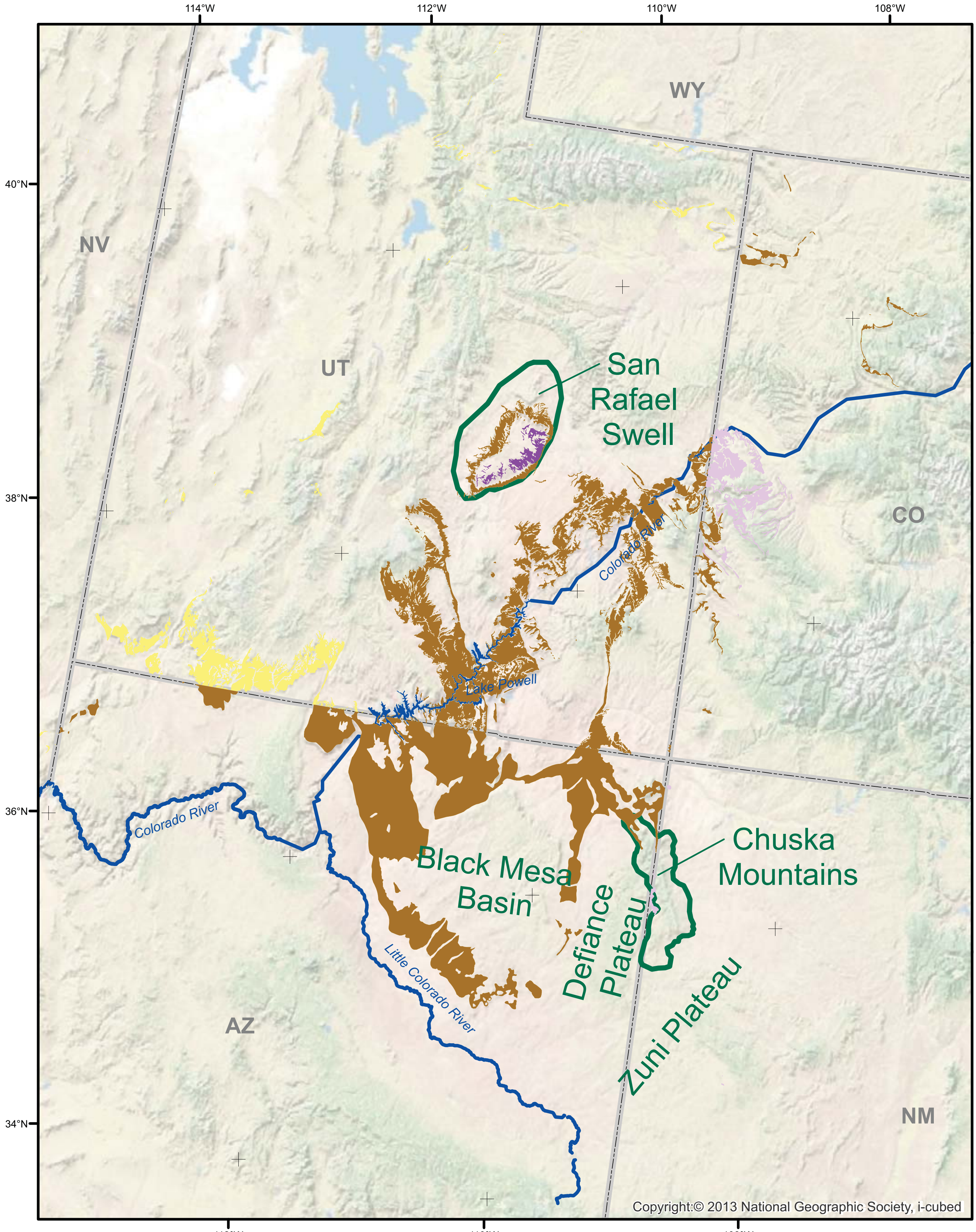
Samples from the upper part of the Wingate Sandstone south of Moab, Utah, were examined by Rupke and Boden (2013). These outcrops were described as massive, 220- to 420-ft (67- to 128-m)-thick, cross-bedded, fine-grained, subangular, and well sorted aeolian sandstone (Doelling, 2004). Although they showed medium suitability as to friability, they were determined to have a low suitability as a frac sand source because of low purity and fineness of grain size (Rupke and Boden, 2013).

Navajo Sandstone

The Lower Jurassic Navajo Sandstone is the uppermost formation within the Glen Canyon Group in southeastern Utah and northeastern Arizona (Harshbarger and others, 1957; Peterson and Pipiringos, 1979) and is widely recognized over most of the Colorado Plateau (Harshbarger and others, 1957) (fig. 20). The Navajo Sandstone of southern Utah has been correlated with the Nugget Sandstone of the Uinta Mountains and the Aztec Sandstone of southwestern Nevada (Doelger, 1987). The Navajo Sandstone is described as a very pale orange to pale reddish-brown, medium- to fine-grained, subrounded, cross-bedded, quartz sandstone that is generally weakly cemented with calcareous cement (Harshbarger and others, 1957). The unit is characterized by large-scale cross stratification and is typically interpreted as being aeolian in origin (McKee, 1979). The Navajo Sandstone reaches a maximum thickness of 1,400 ft (427 m) in its northwestern extent, thinning southeastward to 15 ft (5 m) northwest of Chinle, Arizona (Harshbarger and others, 1957). The Lamb Point Tongue of the Navajo Sandstone from Kane County, Utah, has been described as having some potential as a frac sand source because of its ≥95 percent silica content and its frosted, well-sorted, and well-rounded to subangular grains (Doelling and Davis, 1989; Doelling, 2004; Biek and others, 2010; Rupke and Boden, 2013).

The Nugget Sandstone is present in northern Utah, southeastern Idaho, and western Wyoming (Doelger, 1987). It has been correlated not only with similar aeolian sandstones of the Navajo Sandstone but, by some workers, with the entire Glen Canyon Group of the Colorado Plateau (Poole and

Figure 20. Surface exposures of Lower Permian and Lower Jurassic quartzose sand source units in the southwestern region that have limited potential suitability for use as frac sand. Units shown are the Lower Permian Cutler Formation (purple) that includes the White Rim and Cedar Mesa Sandstone Members, and the Lower Jurassic Glen Canyon Group, undivided (brown) that includes the Wingate Sandstone or the Rock Point Member of the Wingate that was reassigned to the Chinle Formation by Dubiel (1989) (lavender) and the Navajo or Nugget Sandstone (yellow).—Following page



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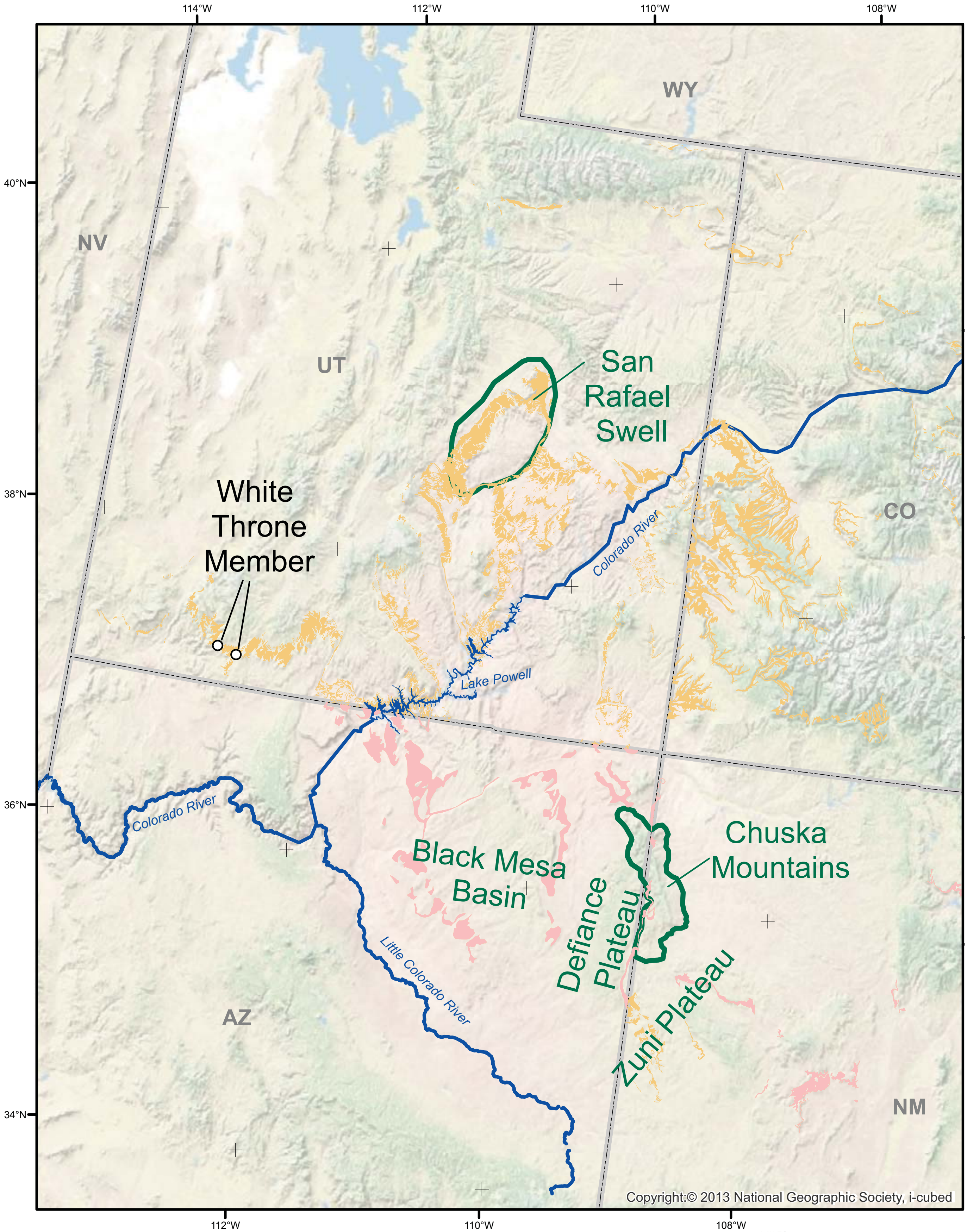

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Figure 21. Surface exposures of Middle Jurassic quartzose sand source units in the southwestern region that have limited potential suitability for use as frac sand. Units shown are in the San Rafael Group and include the White Throne Member (white dots) of the Temple Cap Formation; the San Rafael Group, undivided, that includes the Page Sandstone and Entrada Sandstone (pink); and the San Rafael Group, undivided, that includes the Entrada Sandstone (mustard yellow).—Previous page

Stewart, 1964). The Nugget Sandstone is typically a very fine to fine-grained, subangular to rounded, moderately-sorted to moderately well-sorted subarkose, quartz arenite, or both, that contains <10 percent matrix and <20 percent calcite cement and has abundant medium- to large-scale cross-bedding (Doelger, 1987). The Nugget Sandstone from South Pass, Wyoming, is perhaps relatively well suited for potential use as frac sand, as it is described by Kayser (1964) as an orthoquartzite that is fine to medium grained, with well-rounded and well-sorted grains. Additionally, in the area of the Uinta Basin of Utah, samples of the Nugget Sandstone show ≥95 percent silica content and good friability (Rupke and Boden, 2013). Near Vernal, Utah, its thickness is 510 to 1030 ft (156 to 314 m) (Sprinkel, 2006, 2007). The Nugget Sandstone in the Uinta Basin, where it is in close proximity to oil and gas production, should be tested for crush resistance to further evaluate its potential as a frac sand source (Rupke and Boden, 2013).

White Throne Member

The Middle Jurassic White Throne Member is in the Temple Cap Formation. The Temple Cap Formation is a sandstone of limited geographic extent that occurs as the basal unit of the San Rafael Group that unconformably overlies the Navajo Sandstone in extreme western Kane County and extreme eastern Washington County (Peterson and Pipiringos, 1979), Utah. At the type section in Zion Canyon, Washington County, the Temple Cap Formation is subdivided (in descending order) into the White Throne Member, a 49.7-m (163-ft)-thick, fine-grained, well sorted, cross-bedded sandstone; and the Sinawava Member, a 6.1-m (20-ft)-thick, flat-bedded sandstone, silty sandstone, and mudstone (Peterson and Pipiringos, 1979). The White Throne Member is a cliff-forming unit that is exposed in canyon walls in Johnson Canyon, Mount Carmel Junction, and Zion Canyon; and it pinches out westward into a thick deposit of the otherwise underlying Sinawava Member (Peterson and Pipiringos, 1979). The White Throne Member in Kane and Washington Counties, Utah (fig. 21, pl. 1), is proposed as having a high potential as a future frac sand source (Rupke and Boden, 2013; Rupke, 2014; Rupke and Boden, 2014). The unit has a relatively fine size distribution with a potential to provide a 30/50- or 40/70-sized product, at least a 97-percent silica content, and marginal roundness when compared to the ideal frac sand sources; yet, more testing such as crush resistance is needed to determine the true degree of suitability as frac sand (Rupke and Boden, 2013; Rupke, 2014; Rupke and Boden, 2014).

Page Sandstone

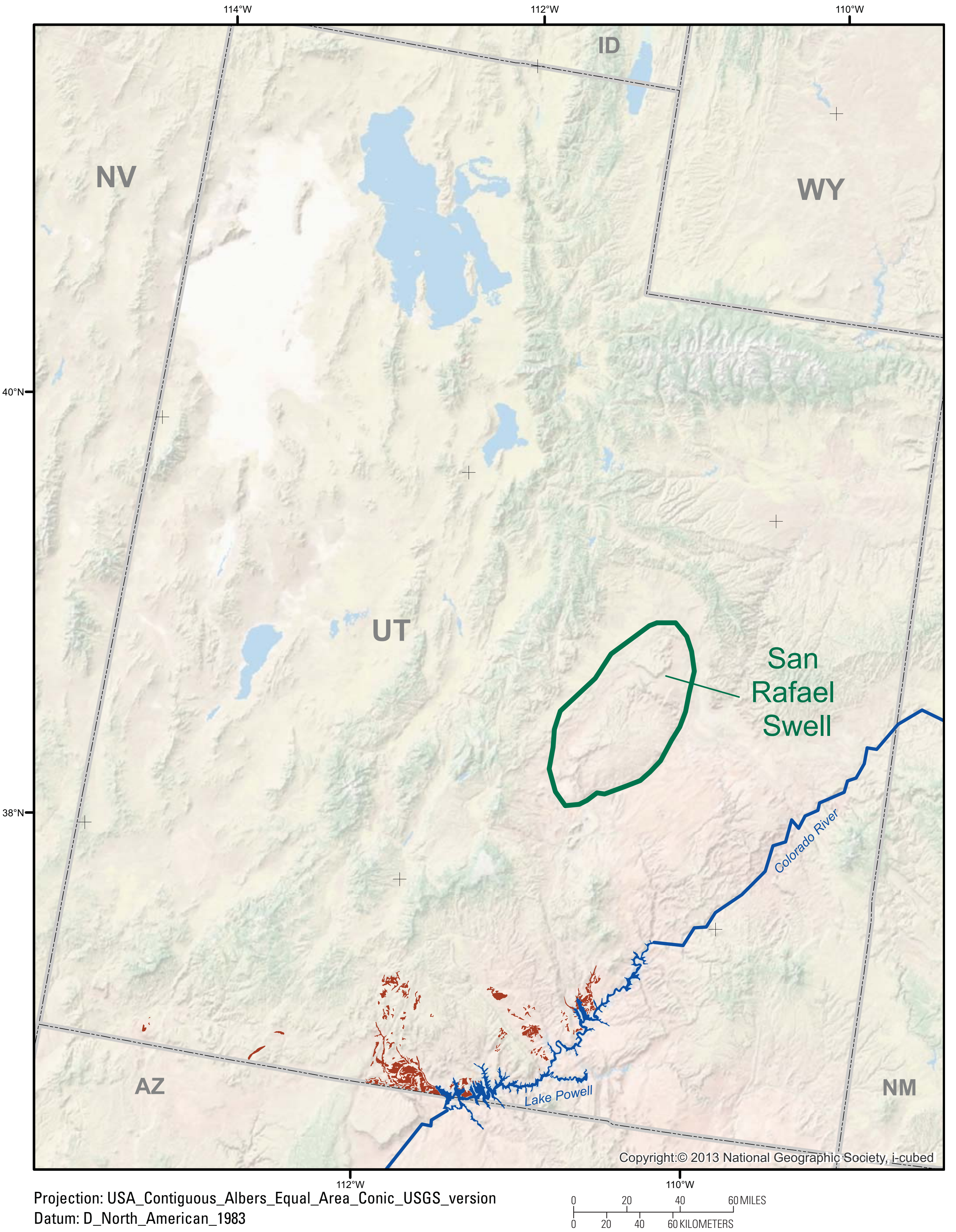
The Middle Jurassic Page Sandstone is a basal unit in the San Rafael Group and has a limited geographic extent from south-central Utah to north-central Arizona (Peterson and Pipiringos, 1979) (fig. 21). The Page Sandstone unconformably overlies the Navajo Sandstone. The Page Sandstone is a cliff-forming, cross-bedded, fine-grained, well-sorted, red or light-gray sandstone with a thickness of 55.8 m (183 ft) at the type section on Manson Mesa, near Page, Arizona (Peterson and Pipiringos, 1979). The unit thickens to 88.7 m (291 ft) southward for about 18 km (11 mi) beyond Page (Peterson and Pipiringos, 1979). Northwestward from Page, the Page Sandstone is subdivided (in descending order) into the Thousand Pockets Tongue and the Harris Wash Tongue (Peterson and Pipiringos, 1979). The Thousand Pockets Tongue is the most prospective sandstone in the Page Sandstone for a potential frac sand source because of its ≥95 percent silica content (Rupke and Boden, 2013).

Entrada Sandstone

The Middle Jurassic Entrada Sandstone is within the San Rafael Group in southeastern Utah, northwestern Arizona, northwestern New Mexico, and southwestern Colorado (Baker and others, 1936; Harshbarger and others, 1957) (fig. 21). The formation in this area comprises three members (in descending order): the upper cross-bedded sandy member; the medial silty member; and the lower cross-bedded sandy member that is, in part, aeolian in origin (Harshbarger and others, 1957). Facies equivalents to these three members are recognized in the type section of the Entrada Sandstone on Entrada Point in the San Rafael Swell of southeastern Utah (Harshbarger and others, 1957). These upper and lower clean sandy members consist of moderate reddish orange to grayish orange pink, cross-bedded, medium- to fine-grained, subrounded to subangular quartz, with concentrations of coarse-grained, well-rounded amber-colored and white quartz sandstone (Harshbarger and others, 1957). The upper clean sandy member reaches a maximum thickness of 375 ft (114 m) at Navajo Point, Utah; and the lower clean sandy member reaches a maximum thickness of 332 ft (101 m) at Lupton, Arizona (Harshbarger and others, 1957).

Samples of the Entrada Sandstone from Utah that were examined by Scholle (1979) are characterized as texturally and mineralogically supermature and interpreted as having been deposited in high-energy settings such as beaches and aeolian dunes. These samples are described as very well sorted, very well rounded, quartz arenite or orthoquartzite containing <5 percent detrital clay (Scholle, 1979). One sample of the

Figure 22. Surface exposures of Quaternary aeolian dune sands in the southwestern region that have limited potential suitability for use as frac sand. These sands (deep red) are at the surface on the northwest rim of the Colorado River at Lake Powell in southern Utah.—Following page



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Entrada Sandstone from southeast Kane County, Utah, where it has a thickness of 330 to 950 ft (101 to 290 m) (Doelling and Willis, 2006), was examined for suitability as frac sand by Rupke and Boden (2013). Although the sample indicated medium suitability as to friability, the unit was determined to have a low suitability as a frac sand source because of low purity and fineness of grain size (Rupke and Boden, 2013).

Quaternary Aeolian Dune Sands

Quaternary aeolian dune sands in Kane and Washington Counties, Utah (fig. 22, pl. 1), are proposed as a high-potential future frac sand source (Rupke and Boden, 2013; Rupke, 2014; Rupke and Boden, 2014). Samples of these unconsolidated sands have a relatively fine size distribution with a potential to provide a 30/50- or 40/70-sized product, at least a 97-percent silica content, and marginal roundness when compared to the ideal frac sand sources; yet, more testing such as crush resistance is needed to determine the true degree of suitability as frac sand (Rupke and Boden, 2013; Rupke, 2014; Rupke and Boden, 2014).

GIS Data Delineating Frac Sand/Proppant Sand Source Units in the United States

Description

The map extents for sand source units featured in this study were derived from a newly compiled GIS dataset that is provided as a component of this report. This dataset displays the surface areal extent of the primary stratigraphic units that are mined for frac sand or that have been specifically mentioned in the published literature or on Web sites as potential frac sands or substrate sands used in resin-coated proppant manufacture. The shapefiles of this dataset (FracSand_Geology.shp) show the extent of selected bedrock geologic units that generally correspond with those designated in the State Geologic Map Compilation (SGMC) project (J.D. Horton, C.A. San Juan, and D.B. Stoeser, unpub. data), a nationwide compilation of modified and updated digital map data of bedrock geology of individual States (http://mrdata.usgs.gov/geology/state/map.html) that is in preparation by the U.S. Geological Survey. These State maps are at 1:500,000 to 1:1,000,000 scale, so they frequently contain combined units, otherwise the units on the map would be thinner or smaller than can be portrayed. As a result, frac sand potential is overrepresented on map figures and plate 1 because the units frequently include other lithologies not suitable for frac sand. See Appendix 1 for a detailed explanation of the units mapped.

Dataset Constraints

The map compilation of units limited to a specific component lithology is more challenging than it might appear. As indicated in the metadata contained in the GIS, local refinements were incorporated into the dataset, especially for the St. Peter Sandstone-bearing units in Iowa. It is important to note that the original shape files showing the areal extent of units and the unit descriptions, in most cases, represent combined or "undivided" rock units. Additionally, it is necessary to be aware that certain units have variously been classified as "Group," "Formation," or "Member" by different authors over time and that such usage in this map is a reflection of its usage by the authors of each original map used in this compilation.

Bedrock geologic maps are typically compiled by grouping rocks by formation, not by similar lithology (rock-type, such as sandstone, limestone, shale, or granite). When in search of frac sand, only units containing mostly pure quartz-rich sandstone are of interest. At State-scale, mapping each lithology is unrealistic, as the units are too small or too thin to depict on the map. More often than not, the units shown on the map contain both the units containing frac sand and age-related units that do not contain frac sand. Therefore, the areal extent featured on the map frequently overrepresents the area where frac sand actually occurs.

Similarly, if a unit of interest has limited areal extent, it may be omitted from a State-scale map. This is just a process of simplification and is necessary when trying to show complicated geology at very small scales. Therefore, it is entirely possible for a frac sand-bearing unit to be missing from the map. A detailed account of the lithologic units selected for inclusion in the frac sand GIS map data for the conterminous United States and all GIS-derived figures and plate 1 is provided in Appendix 1.

Examples from Wisconsin

The following examples from Wisconsin illustrate the lesser degree of precision as to map area that results from such lumping of stratigraphic units with similarly aged units of various lithologies. The lithologic descriptions used in the Wisconsin State map data presented below are from Mudrey and others (1987).

As mapped using the preliminary SGMC data, the St. Peter Sandstone is included in the map unit designated as the Ordovician Ancell Group. The Ancell Group is described as an orthoquartzitic sandstone with minor limestone, shale, and conglomerate that contains the Glenwood Formation and the St. Peter Sandstone (U.S. Geological Survey Mineral Resources Online Spatial Data, 2014). Also, in Wisconsin, only the Tonti Member of the St. Peter Sandstone is a frac sand host. The Tonti Member may not occur everywhere that the St. Peter appears. At State-scale, only the more generalized St. Peter Sandstone is mapped; therefore, the exact extent of the Tonti Member is not differentiated from the rest of the St. Peter Sandstone. For that reason, the area mapped as frac sand potential is overrepresented because it is not limited to the Tonti Member of the St. Peter Sandstone.

The unit labeled “Cambrian, undivided” is described as a sandstone with some dolomite and shale, undivided, that includes the Trempealeau, Tunnel City, and Elk Mound Formations (U.S. Geological Survey Mineral Resources Online Spatial Data, 2014). Within this undivided set of “formations” shown on the SGMC map, the Elk Mound “Formation” was designated by Ostrom (1966) as the Elk Mound Group that is subdivided in ascending order into the Mount Simon, Eau Claire, and Wonewoc Formations. So, the map extent of the “Cambrian, undivided” consists of a large set of units that includes two units that contain prospective frac sand (the Mount Simon and Wonewoc Formations), but it also includes carbonates that are not frac sand sources (the Eau Claire Formation). In addition, the Trempealeau “Formation” that is included in the “Cambrian, undivided” has otherwise been recognized as a Group that contains the Jordan Formation (a frac sand source) and the St. Lawrence Formation (a carbonate unit). In producing the final map product for this report, where feasible, more detailed maps were used to modify the footprint of units that were originally lumped on the digital State maps.

Ideally, at a minimum, separation of the “Cambrian, undivided” map unit into formations and members would allow better identification of the sand-bearing rocks. Due to the limitations of the current digital data, the more detailed footprints of the frac sand source units within the Jordan Formation (Van Oser Member), the Wonewoc Formation (Galesville Member), and the Mount Simon Formation are completely obscured.

Distribution of All Sand and Sandstone Versus Frac Sand/Proppant Sand Source Units

Using the combined State maps (SGMC), all the units containing sands or sandstone as a primary lithologic component are shown on figure 23. There are some imperfections, such as where the sands (yellow) or sandstones (orange) stop abruptly at State lines (notably all States abutting Nebraska, along the North Dakota-South Dakota State line, west Texas border with New Mexico and Oklahoma, and at the Colorado-Kansas border). These are simply differences in interpretation of what is considered by each State’s geologists or GIS specialists to be important or feasible to show on a map.

Superimposed in other colors on this map are the units that have been identified from the literature and Web sites as being mined for or having potential for use as frac sand or resin-coated sand (fig. 24). It is clear from this figure that, while the country has abundant sand and sandstone, only a very small percentage of those units is potentially suitable as frac sand sources. Neither of these maps takes into account areas that are inaccessible to mining.

Frac Sand/Proppant Industry Activity in North America

Reports of Proppant Industry Activity in the United States

The following discussions include information on geologic units that are either currently mined for frac sand, are currently mined for substrate sand used in the manufacture of resin-coated proppants, or have been considered as potential future sources for use in the proppant industry. The most active States were selected for discussion and are listed in geographic order from the upper and central Midwest, to the south-central, Great Plains, and southwestern regions. Many towns mentioned are shown on plate 1.

Wisconsin

Middle and Upper Ordovician St. Peter Sandstone, Upper Cambrian and Lower Ordovician Jordan Sandstone, Upper Cambrian Wonewoc Formation, and Upper Cambrian Mount Simon Formation are mined for frac sand.

Wisconsin produces “Northern White” sand principally from the following counties: Barron, Chippewa, Dunn, St. Croix, Pepin, Pierce, Buffalo, Eau Claire, Trempealeau, Monroe, Jackson, Clark, and Wood. The mines are located in the unglaciated (“driftless”) area of west-central and southwestern Wisconsin (Brown, 2014). There, the Paleozoic sandstones have been exposed to the surface by the deeply eroding streams that carried meltwaters from Pleistocene glaciers in the northeast into the Mississippi River drainage to the south-southwest (Runkel and Steenberg, 2012). The erosional removal of much of the St. Peter Sandstone has made the Cambrian units more widely accessible near the surface. In portions of the southern outcrop extent, the Jordan Formation has also been removed by erosion leaving a narrow outcrop band on the upper slopes of ridges in the unglaciated areas, in valleys of southern Pierce County, and on the western slope of the Chippewa Valley (Brown, 2014). The Van Oser Member of the Jordan Formation is an excellent producer of 20/40 mesh frac sand (Syverson, 2012). The Wonewoc Formation forms a similar, but wider, outcrop belt on the lower slopes beneath the Jordan (Brown, 2014). To the south and east in the northeastern part of Sauk County, only the upper part of the Wonewoc is exposed at the surface (Clayton and Attig, 1990). The Wonewoc is a good producer of 20/50 mesh frac sand (Syverson, 2012). The Mount Simon Formation has been mined in Clark and Wood Counties for 20/40 mesh frac sand (Syverson, 2012).

Frac sand is also produced from underground mining of the Jordan Formation in Maiden Rock (about 45 miles southwest of Eau Claire) and Bay City, Wisconsin (Jones, 2006; Runkel and others, 2012; Runkel, 2014). Wisconsin Industrial Sand Company (an affiliate of Fairmount Minerals) operates the mine at Maiden Rock, where it simply burrows into the bluffs along the Mississippi River (Jones, 2006, McLeod, 2011).

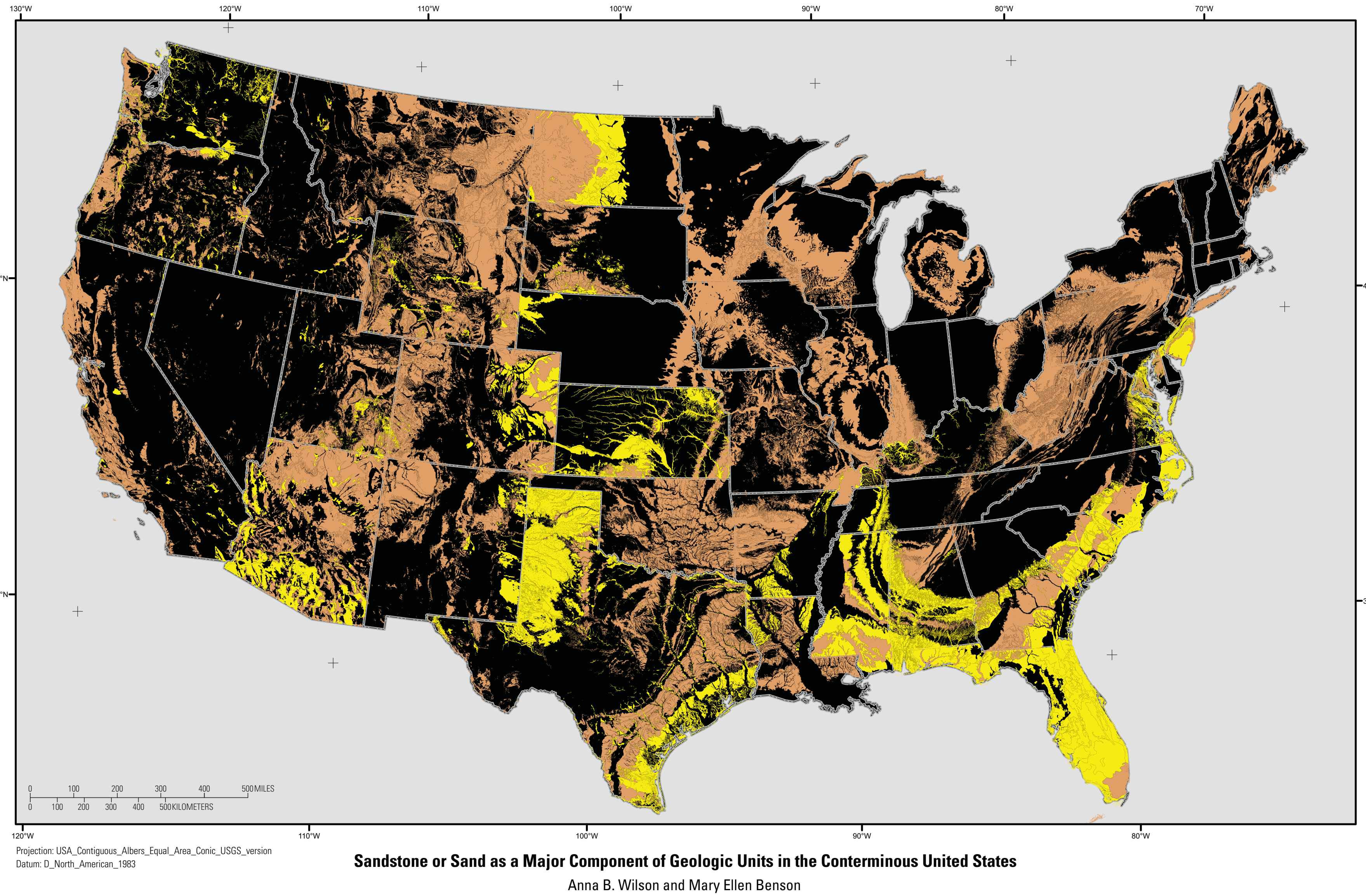

Figure 23. Map of all the units containing sands or sandstone as a primary lithologic component in the conterminous United States. Units shown are unconsolidated sands (yellow) and sandstones (orange) on a black background.

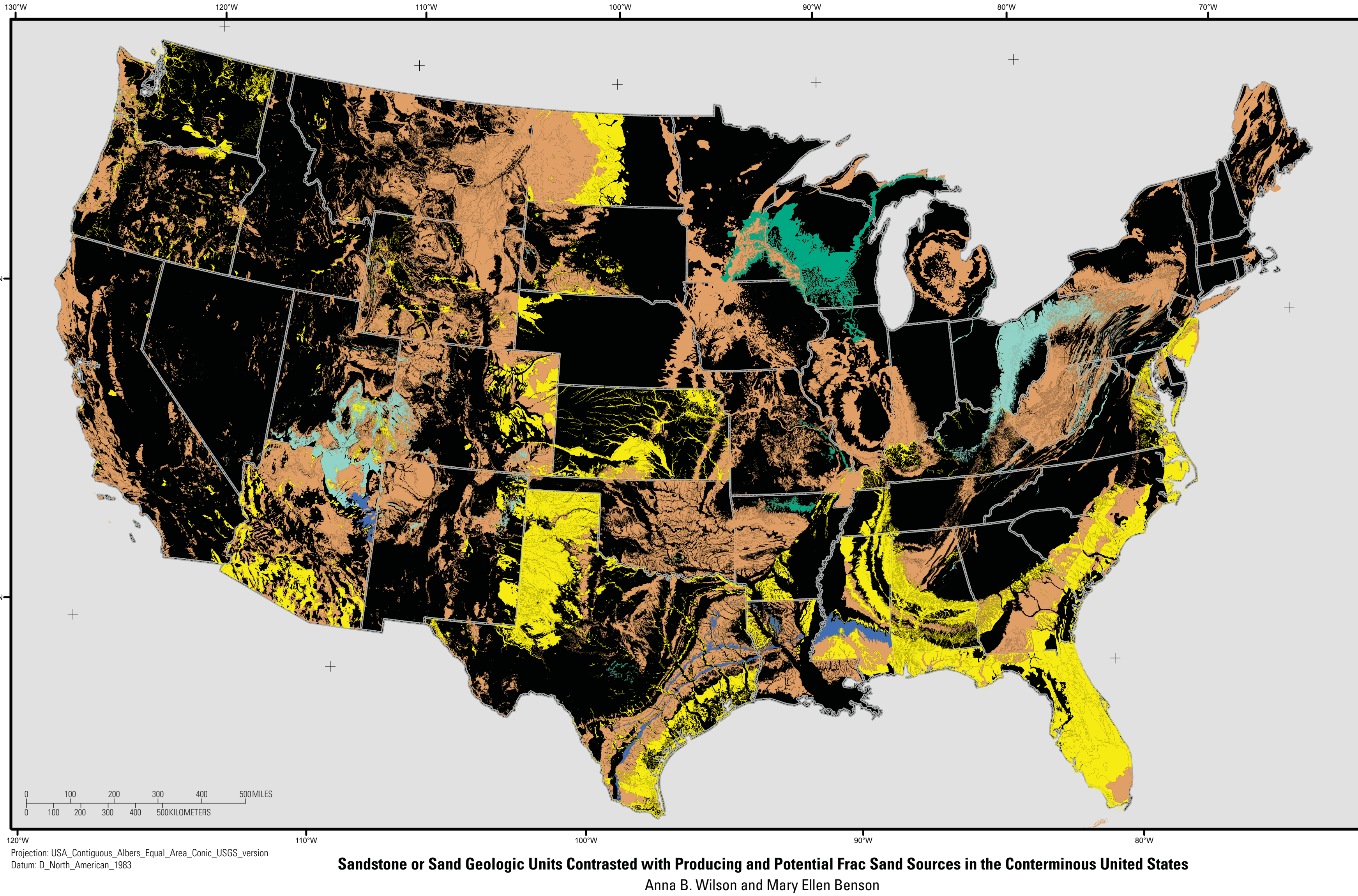

Figure 24. Map of all the units containing frac sand (green), potential frac sand (turquoise), resin-coated sand (blue) sources compared with all other sands (yellow) and sandstones (orange) identified as a primary lithologic component in the conterminous United States.

Minnesota

The Middle and Upper Ordovician St. Peter Sandstone, Upper Cambrian and Lower Ordovician Jordan Formation, and Upper Cambrian Wonewoc Formation are major sources for frac sand in Minnesota. The St. Peter is mined in Kasota and in the Ottawa Township, both in Le Sueur County, along the Minnesota River (Runkel, 2014). The Jordan and Wonewoc are at or near the surface in the Saratoga Township of Winona County, in southeastern Minnesota (Runkel, 2014).

Iowa

Frac sand is produced from the Ordovician St. Peter Sandstone at the Pattison Sand Mine in both surface and underground workings in Clayton County (McLeod, 2011). In 2012, a proposal to mine the Cambrian and Ordovician Jordan Formation of Allamakee County was met with an 18-month moratorium, and the permit request was withdrawn (Libra, 2013; Kitco Metals, 2014). The Wonewoc Formation exposed at the surface in northeastern Iowa is an additional potential source for frac sand (Kline and Osterberg, 2014).

Illinois

Middle and Upper Ordovician St. Peter Sandstone and the Upper Cambrian Mount Simon Formation are frac sand sources. The St. Peter is mined as frac sand in Ottawa, Sheridan, Wedron, and Naplate, in north-central Illinois. The unit is present also in the subsurface in southwestern Illinois, where thicknesses range from 40 to 150 ft (12 to 46 m), and where it is described as white to light-gray, fine- to coarse-grained, well-rounded and frosted quartz sandstone that is weakly cemented, with local beds of sandy dolomite (Nelson and others, 1996).

Michigan

Although not typically mined for frac sand, Wolfe (2013) considers the Middle Devonian Sylvania Sandstone prospective for future use in the fracking industry due to its high silica purity and near-surface depths. Currently, U.S. Silica reports that they mine “frac-capable” sand from the Sylvania Sandstone in Rockwood, Michigan (U.S. Silica, 2014c). The Middle Devonian Sylvania Sandstone is designated as a formation of the Detroit River Group in the Michigan Basin of Michigan and is described as extremely pure glass sand of 20 or more feet (6 or more meters) in thickness probably in Monroe County (Orton, 1888; U.S. Geological Survey National Geologic Mapping Database, 2013).

Highly quartz-pure Quaternary dune sands in Mason County, along the eastern shore of Lake Michigan, are being mined as frac sand. Sargent Sand Company produces 30/70, 30/50, 40/70, and 100 mesh frac sand that meets or exceeds API specifications from its mine in Ludington, Michigan (Sargent Sand, 2014). These “lake sands” have a crush resistance of 7-k and are used in the Marcellus shale play (Thomas Watkins, Universal Well Services, Inc., oral commun., November 17, 2014).

Ohio

Although the Upper Cambrian Mount Simon Formation frac sand source extends into Ohio, it is only in the deep subsurface of east-central Ohio in the Waverly arch area and west of the Ohio-West Virginia hinge zone (Ryder, 1992; Ryder and others, 1996; Saeed and Evans, 2012).

The Lower Mississippian Black Hand Sandstone Member of the Cuyahoga Formation contains silty and conglomeratic facies, but also occurs as a massive, coarse-grained, 98-percent silica sandstone as much as 100 ft (31 m) thick that is mined as a frac sand, as well as an industrial sand, in Knox County (Wolfe, 2013).

The Middle Devonian Sylvania Sandstone of the Detroit River Group in Ohio and Michigan is a potential future source of frac sand (Wolfe, 2013). It is described as extremely pure glass sand of 20 or more ft (6 or more m) in thickness in Lucas and Wood Counties, Ohio (Orton, 1888; U.S. Geological Survey National Geologic Mapping Database, 2013).

Missouri

Middle and Upper Ordovician St. Peter Sandstone crops out in a narrow belt that parallels the Mississippi River from Scott County in the southeast northward through Jefferson County; just southwest of St. Louis, it turns westward and follows the bluffs of the Missouri River into Montgomery and Gasconada Counties, and then proceeds in only scattered outcrops farther westward (Davis, 2011). In Perry and Cape Girardeau Counties of southeastern Missouri, the St. Peter consists of thick-bedded to massive, cross-bedded and ripple-marked, nearly 100 percent white to light-brown, fine- to medium-grained, well-sorted, well-rounded and frosted quartz sandstone that ranges in thickness from 210 to <50 ft (64 to <15 m), thinning to the east and south (Nelson, 1996). West and south of St. Louis, in St. Charles, Franklin, and Jefferson Counties, it is mined as frac sand in Pacific, Festus, Crystal City, Augusta, and Pevely; and it was also mined farther south in Perry County (Davis, 2011, 2014; Sun Times News, 2013). The Missouri Department of Natural Resources estimates St. Peter Sandstone reserves of 3.8 trillion short tons in the State (Missouri Department of Natural Resources, 2014).

The Upper Cambrian Lamotte Sandstone (a stratigraphic equivalent of the Mount Simon Formation of the upper Midwest) is exposed along the northeastern flanks of the Ozark uplift in the Farmington and Oak Grove areas of southeastern Missouri (Houseknecht and Ethridge, 1978). The Lamotte is being mined in Ste. Genevieve County for use as frac sand by Summit Proppants, Inc. (Summit Proppants, 2013).

Arkansas

Middle and Upper Ordovician St. Peter Sandstone is well exposed in Madison, Carroll, Newton, Boone, Searcy, Marion, Baxter, Stone, Izard, Sharp, and Independence Counties in northern Arkansas along the drainage of the White and Buffalo Rivers (Stroud and others, 1969). Outcrops in the valley of the Buffalo River in northeastern Newton and northern Searcy Counties were found to have diagenetic grain overgrowths that reduced the sphericity/roundness needed for frac sand (Glick and Frezon, 1953). Farther east at Guion, in Izard County, just east of the White River, the unit is mined for frac sand by Unimin Corporation in an underground operation (Encyclopedia of Arkansas, 2014), and a resin-coating plant was built there in 2012 (Franco, 2013). Other sands in the State that are being mined and marketed as frac sand include the dredging of modern sands from along the Arkansas River in Sebastian County by Arkhola Sand and Gravel Company and the Quaternary deposits adjacent to the Arkansas River that are mined by Delta Company in eastern Pulaski County (Encyclopedia of Arkansas, 2014).

Oklahoma

Middle Ordovician Oil Creek Formation is within the Simpson Group in Oklahoma (Decker and Merritt, 1931). This sandstone unit was referred to by Buttram (1913) as "glass sands" of the Simpson Group where it occurs in an outcrop belt flanking the Arbuckle Mountains in Murray and Johnston Counties of southern Oklahoma. These are described as pure white sand beds that are free from mud and other fine detritus, relatively uniform in grain size, and sub-rounded due to long continued sorting action; and they are interpreted to have been deposited in a beach or near-shore environment (Buttram, 1913). The Simpson Group glass sand is exposed in these eight general areas in the Arbuckle Mountains: Southern belt on the south side of the mountains that includes Phillips Creek, Cool Creek, Crusher, Oil Creek, and Mill Creek sections; Delaware Creek area; Roff area; Hickory area; Mill Creek area; Nebo area; Buckhorn/Sulphur area; and Davis area (Buttram, 1913). The sands from the exposed section on Oil Creek in sec. 17, T. 3 S., R. 4 E. consist of 76 ft (23 m) of a good grade of glass sand within a 100-ft (31-m)-thick basal sandstone that rests on the Arbuckle Limestone (Buttram, 1913). U.S. Silica operates a silica sand mine and plant that produces frac sand in the Oil Creek Formation at Mill Creek on Highway 1 (U.S. Silica, 2014d).

The Middle Ordovician Burgen Sandstone that is exposed in the Tahlequah area along the north bank of the Illinois River in Cherokee County, northeastern Oklahoma, is correlated with the St. Peter Sandstone and is described as a "glass sand" of about 50 ft (15 m) thick (Buttram, 1913). It is a massive, poorly cemented, moderately fine-grained, rounded, light-brown, pure silica sandstone (Taff, 1905). Cram (1930) suggested that the Burgen may be correlative with the basal sandstone of the Oil Creek Formation of the Simpson Group.

Although Buttram (1913) reported on additional sources of "glass sand" (high-silica sand) from the basal Lower Cretaceous Trinity Sand in southeastern Oklahoma from Love to McCurtain Counties along the southern base of the Arbuckle and Ouachita Mountains, the Trinity is not a likely source for frac sand because the unit has a high clay content, is very heterogeneous, and does not extend for long distances.

Texas

Frac sand that is referred to as "Brown" or "Brady" sand is mined from the Hickory Sandstone Member, which is the basal member of the Riley Formation, at Voca on the northwestern flank of the Llano uplift (Kyle and McBride, 2014). Other mining operations in the Hickory Sandstone Member occur at Erna and Fredonia, Texas. This production of "Brown" sand is a lower cost alternative to the "Northern White," and it is located close to the Barnett petroleum shale plays in the Ft. Worth Basin and several other major plays in the region (Kyle and McBride, 2014).

Nebraska

Highly mature modern river sand derived from aeolian fields of reworked glacial-outwash in Nebraska has high potential as a sand source in the proppant industry (Epley, 2014). Such deposits are in the area near Genoa, in Nance County, where as much as 125 million tons of sand has amassed over 75 years of dredging the canal that leads into the Loup hydroelectric power station (Epley, 2014). The source of the sand is the Loup River. It accumulates in the utility plant's settlement basin. One to two million tons of this sand and associated sediments must be removed per year in order to keep the water flowing to the district's two hydroelectric power plants at Monroe and Columbus (Epley, 2014). Since 1937, this sand has been pumped to either side of a 2-mile-long canal until more land was purchased for storage (Epley, 2014). Currently, there is 100 million to 125 million tons of sand piled up next to the canal (Epley, 2014). The rounded shape of the sand is attributed to thousands of years of flowing through the Loup riverbed (Epley, 2014). Preferred Sands of Genoa purchased the operation in 2007 and is using it in the manufacture of resin-coated proppant (Shale Reporter, 2013).

South Dakota

South Dakota Proppants, LLC, a fledgling frac sand company, has announced plans to build a silica mine, a frac sand processing plant, and a transport hub in a national forest, about 14 mi (23 km) from Hill City, in the Black Hills,

Figure 25. Index map of provinces, place names, and physiographic features mentioned in the text for Canada.

where it will be strategically located within 300 mi (483 km) of unconventional oil and gas producing basins (Hirji, 2014). This mega-facility would be operational in 2016. The target unit at this new proposed operation is the Upper Cambrian Deadwood Formation (Thomas Marshall, South Dakota Geological Survey, oral commun., July 02, 2014). Although studies of the Deadwood Formation in areas of the Black Hills have suggested frac sand potential for the basal sands (Ching, 1973; Huq, 1983), a 2014 study by the South Dakota Geological Survey contradicts this. The 2014 survey of potential frac sand units in South Dakota found that, although a portion of grains from some samples of the Deadwood Formation would meet some of the API-recommended criteria, the Deadwood Formation, in general, is not deemed to be a prospective frac sand source (Marshall and others, 2014).

Utah

In a preliminary report by the Utah Geological Survey, it was proposed that the units with the highest potential for use as frac sand include the Lower Permian White Rim and Cedar Mesa Sandstone Members in Emery County near the popular recreational area of the San Rafael Swell, the Middle Jurassic White Throne Member of the Temple Cap Formation in Kane and Washington Counties, and the Quaternary aeolian dune sands in Kane and Washington Counties, Utah (Rupke, 2014).

> "Although the White Rim/Cedar Mesa Sandstones of Emery County had the best size characteristics, most of the samples had marginal roundness, and much of the unit is located in the San Rafael Swell, a popular recreational area that could complicate permitting. Both the White Throne Member and aeolian dune sands, which were sampled in Kane and Washington Counties, showed potentially suitable size distributions, but the Quaternary dune sands may have the highest potential because they are unconsolidated, which would require less processing." (Rupke, 2014, p. 7)

> "These units could potentially provide a 30/50 or 40/70 sized frac sand product, but additional testing, particularly crush resistance testing, would be required to determine if they are fully suitable for use as frac sand." (Rupke and Boden, 2014, p. 40)

Arizona

The Pliocene Bidahochi Formation in the Black Mesa Basin area of northeastern Arizona consists of fluvial and lacustrine deposits and basaltic volcanic rocks (Repenning and Irwin, 1954). An informal sandstone member within the upper part of the formation has been identified in the Sanders area as a frac sand of limited use (Zdunczyk, 2007). In 2005, the Trabits Group developed leases associated with a montmorillonite clay mine that had, as overburden, an unconsolidated, well-rounded sand that they interpreted as a paleochannel that was exposed in Tolapai Draw just east of Sanders. This deposit was proven to contain more than 17 million tons of recoverable sand of API frac sand quality (Trabits Group, 2014). The sandstone member has a maximum thickness of approximately 600 ft (183 m) near Greasewood (Kiersch and Keller, 1955). In 2011, the property was purchased by Preferred Sands, who claimed a reserve of 130 million tons with a potential to mine 2 million tons per year (Arizona Geology, 2012). Three quarries believed to be mining the frac sand near Sanders are the Houck Silica Sand Pit north of Interstate Highway I-40 and the Cheto Mine 1 and the Cheto 2 south of I-40 (Arizona Geology, 2012). Preferred Sands was expected to open a resin plant at the Sanders location in 2013 (Arizona Geology, 2012).

Reports of Proppant Industry Activity in Canada

Canada is pursuing its own domestic frac sand resources for use in more efficiently developing their petroleum shale basins (fig. 6). Exploration for frac sand source units has occurred in Alberta, British Columbia, Manitoba, Northwest Territories, Saskatchewan, and Yukon. Figure 25 shows geographic features of Canada that are discussed in this section.

Alberta

- Peace River: The Peace River Frac Sand Quarry, which is owned and operated by Canadian Silica Industries, produces frac sand from the Lower Cretaceous Paddy Member of the Peace River Formation. The Peace River Frac Sand Quarry reportedly has a total annual capacity of 500,000 tonnes of silica sand. This operation is located in close proximity to the Horn River, Montney, and Cardium Basins and is central to the frac sand market within northwestern Alberta (The Wall Street Journal, 2014).
- Fort McMurray: A frac sand deposit known as the Firebag deposit is north of Fort McMurray (Rock Products, 2014a). Athabasca Minerals has a prospective frac sandstone deposit in this area with an estimated capacity of 1,000,000 tons per year (tpy) (Claim Post Resources, Inc., 2013). Preliminary testing indicates that the Firebag sand meets or exceeds API/ISO specs for frac sand. A location that is 1,200 mi (1,931 km) closer to key Canadian markets makes this project very advantageous (Shaw, 2014).

British Columbia

- The Rocky Mountain Foothills between Mackenzie and Fort St. John: The Middle to Upper Triassic Liard Formation, the Upper Triassic Charlie Lake Formation, and the Upper Jurassic to Lower Cretaceous Monteith Formation and Lower Cretaceous Monach Formation of the Minnes Group are the most prospective bedrock units assessed for potential frac sands in the province (Hickin and others, 2010). The Liard Formation is mainly a calcite-cemented, fine- to medium-grained, well-rounded to subrounded to subangular, 90-percent quartz arenite of marine shoreface origin (Hickin and others, 2010). The Charlie Lake Formation is a calcite-cemented, fine- to medium-grained, well-rounded to subrounded, feldspathic arenite of marine intertidal origin (Hickin and others, 2010). The Monteith Formation is a silica-cemented, fine- to medium-to coarse-grained, subangular to subrounded, 95-percent quartz arenite of deltaic origin (Hickin and others, 2010). The Monach Formation is a medium- to coarse-grained sand and coarse to granule conglomerate, rounded to subrounded, 95-percent quartz arenite of deltaic origin (Hickin and others, 2010).

- Northeast of Fort Nelson: Unconsolidated deposits with good potential as frac sands include the Komie glaciofluvial delta deposits on the western edge of the Horn River Basin (fig. 6) (Hickin and others, 2010).

- Dawson Creek: Unconsolidated deposits with good potential as frac sands include the Redwillow glaciofluvial delta south of Dawson Creek (Hickin and others, 2010).

- Southeast of Fort Nelson: Unconsolidated deposits with good potential as frac sands include the aeolian deposits of the Fontas Dune Field southeast of Fort Nelson (Hickin and others, 2010).

- Golden: Moberly expanded its glass sand mine for potential frac sand with an estimated capacity of 300,000 tpy (Claim Post Resources, Inc., 2013).

- Prince George and Nelson: Stikine Energy Corporation has two active frac sand exploration projects, the Nonda and Angus projects, each having an estimated capacity of 1,000,000 tpy (Claim Post Resources, Inc., 2013). These are north of Prince George near the Yukon border (Levson and others, 2012). These frac sand projects will require processing that includes crushing, liberation, and cleaning and sorting (Stikine Gold, 2014). The Nonda project is 150 km west of the Horn River Shale Basin, consists of a quartz-pure sandstone in 40/70 and 100 mesh sizes that is very homogeneous and has a surface exposure >11.5 km × 1 km (Stikine Gold, 2014). The Angus project is 200 km south of the Montney Shale Basin, consists of quartz-pure sandstone in 20/40, 30/50, and 40/70 mesh sizes that has a surface exposure of >5 km × 1 km (Stikine Gold, 2014).

Manitoba

- Seymourville: Claim Post Resources, Inc., is developing a surface frac sand deposit in the Seymourville area that is targeted for production in 2015, with estimated capacity of 400,000–1,200,000 tpy. The company has combined the Gossan and Char Crete leases into a single 2.5 mi^2 project on east shore of Lake Winnipeg, northeast of Winnipeg, Manitoba. These leases are across the lake from Black Island, which has had historical production of white silica sand from a quarry on its southeastern shoreline (Claim Post Resources, Inc., 2013).

- Northern Manitoba: Vickory Nickel, Inc., has a prospective frac sand deposit with an estimated capacity of 500,000 tpy that is 60 m (197 ft) below rock within a nickel mine (Claim Post Resources, Inc., 2013).

Northwest Territories

- Fort Liard: Silica North Resources, Ltd., has an active frac sand exploration project (Levson and others, 2012).

- Mackenzie River: Less than optimally accessible quartz-rich sandstone occurs along the Mackenzie River (Proterozoic Katherine Group and Cambrian Mount Clark Formation), and potentially accessible units are at Great Slave Lake (Proterozoic Preble, Kluziai, and Hornby Channel Formations and the Cambrian Old Fort Island Formation) (Levson and others, 2012). Also, Quaternary sand units with high frac sand potential include sand dune deposits derived from older glaciofluvial or sandy glaciolacustrine sediments, and (or) sandy bedrock units (examples of these include the reworked sand units located along the Mackenzie River in the Fort Good Hope, Mountain River, Tulita, Keele River, and Fort Simpson areas) (Levson and others, 2012). In addition, the sandy glaciofluvial deposits along the Liard Highway and paleobeach ridges and dunes along the North Arm of Great Slave Lake are considered units with high frac sand potential (Levson and others, 2012).

Saskatchewan

- West of Flin Flon, Manitoba, which is on the border with Saskatchewan: Hanson Lake Sands has a frac sand deposit with an estimated capacity of 800,000 tpy (Claim Post Resources, Inc., 2013).

- Winn Bay: Preferred Sands acquired Winn Bay Sand in 2011 (Snyder, 2013). This deposit occurs in sandstone of the Ordovician Winnipeg Formation (Levson and others, 2012).
- Lloydminster: Canfrac Sands, Ltd., transports about 50,000 to 100,000 tons of frac sand per year from this deposit (Snyder, 2013).

Multiple Provinces

Canadian stratigraphic units with future frac sand potential exist in the Liard River Valley in British Columbia, Yukon, and Northwest Territories (Carboniferous Mattson Formation and Cretaceous Sikanni, Scatter, and Dunvegan Formations) (Levson and others, 2012).

Resource Development of Frac Sand in the United States

Mining, Processing, and Transportation

Ideally, frac sand mines are open pit quarries with minimal overburden in which loosely cemented to friable sand is often removed by large excavators or power shovels. Commonly, it may be necessary to include blasting, along with additional overburden removal techniques. Following excavation, mined portions of the pit are backfilled. As well as open pit mining, other types of mining may include contour mining, underground mining, and hydraulic dredging (Wisconsin Department of Natural Resources, 2012).

In unusual cases, frac sand is mined by underground methods. One of the few examples is Unimin's underground mine in Arkansas, where they excavate friable St. Peter Sandstone. In this operation, the room-and-pillar method is used in which rooms are cut into the rock being mined and pillars are left standing to support the mine (Encyclopedia of Arkansas, 2014). Another example of underground mining of frac sand is in the Maiden Rock and Bay City areas of Wisconsin where the Jordan Formation is extracted (Runkel and Steenberg, 2012).

Once removed from the mine, friable sand is transported by truck or conveyor belt to either on-site or distant processing plants where it is washed, dried, screened, sorted into different grades, and shipped or stored (Wisconsin Department of Natural Resources, 2012). In the case of more tightly cemented sandstone, the raw material may be disaggregated by crushing, high-pressure water-jetting, or grinding before washing and sorting. The raw product may be directly transported to the market by railroad, barge, or truck, or it may undergo coating treatments before being ready for market (Maslowski, 2012). Sand that is unsuitable for fracking is separated and sold for other uses (Geology, 2013).

Environmental Issues

Common environmental concerns of mining, processing, transport, storage, and application of frac sand or other proppants at the well site include water-use volume, water quality, air quality, noise, scarring of terrain, devaluation of real estate, impact of transportation on road infrastructure, and increased traffic congestion (Maslowski, 2012). Permits are required prior to developing a mine and processing plant, and State, county, and local jurisdictions issue and enforce regulations.

Water use and quality controls related to silica sand mining and processing include the role of water in mining and processing, reuse and treatment of water, mitigation of potential surface and groundwater contamination, and monitoring of water quality (U.S. Silica, 2014b). Concerns are growing about whether water shortages in aquifers are being exacerbated by the volume of water consumed in hydraulic fracturing operations (Rock Products, 2014d).

Air quality controls related to silica sand mining, processing, and transportation include fugitive dust and emission sources and controls, characteristics of particulates, and air quality monitoring. There is the potential health hazard of inhaling silica dust that is classified by the Occupational Safety and Health Administration (OSHA), in regulation 29 CFR 1910.1200, as a human carcinogen that may be generated during the manufacture, handling, and use of frac sand and the coated substrate sand proppants (U.S. Silica, 2014b).

The phenolic resin commonly used in the manufacture of coated proppants contains traces of formaldehyde that is also listed by OSHA as a potential human carcinogen (29 CFR 1910.1048), which, in the form of concentrated dust, can also be combustible and can become a potential fire hazard (U.S. Silica, 2014b). Neither silica dust nor the phenolic resin dust is considered to be an ecotoxin (toxic to the environment) (U.S. Silica, 2014b).

Transportation controls include options for operations, material transfer processes, mitigation of impacts on road infrastructure, noise, and traffic congestion. These concerns especially relate to delivery of the product to the well site, as the typical truck hauls about 50,000 pounds or 25 tons of sand and many hydro-fracking treatments use more than one truckload (Maslowski, 2012).

Reclamation of sand mines requires reclamation plans, reclaimed site inspection, and monitoring. Land reclamation is the responsibility of the mining company, but the costs are generally passed on to the consumer (Wisconsin Department of Natural Resources, 2012).

Regulation

Frac sand mining companies must abide by rules limiting mining on publicly owned lands and laws protecting streams, wetlands, air quality, and water quality, and by zoning laws and reclamation requirements. States and local jurisdictions vary widely as they evolve toward a balanced approach to the growing commercial development of their frac sand resources and their need for stewardship of their land and environment. Among these, the States play a major role in regulation of mining activity. The examples presented below are from the State of Wisconsin Department of Natural Resources (WDNR), which is on the fast track in developing their frac sand resources.

- Air: Mines and processing plants are required to obtain State air permits that implement Federal regulations under the Clean Air Act. All mines must have a fugitive dust control plan that details how they will prevent dust across the site. Facilities that dry sand are required to stay under the U.S. Environmental Protection Agency (EPA) levels for particulate pollution and monitor air quality on site. Silica exposure is a public health concern, and stray dust has been a source of complaints, so WDNR has been sending information to mine operators on how to control it (Wisconsin Department of Natural Resources, 2012)
- Water: All mines are required to comply with State statutes on water pollution control and drinking water protection that follow Federal regulations of the Clean Water Act and the Safe Drinking Water Act. Mines are required to obtain stormwater and wastewater permits. Those using large quantities of water must have a high-capacity well permit. Facilities near wetlands or surface waters must comply with additional WDNR and U.S. Army Corps of Engineer regulations (Wisconsin Department of Natural Resources, 2012).
- Endangered and Threatened Species: Mining needs to comply with Section 7 of the Federal Endangered and Threatened Species Act administered by the WDNR and the U.S. Fish and Wildlife Service (Wisconsin Department of Natural Resources, 2012).
- Worker Health and Safety: Producing mine operators must comply with the Federal Mine Safety and Health Administration guidelines (Wisconsin Department of Natural Resources, 2012).
- Local regulations: Local governments exert control over mining operations through zoning, but many mines are in towns that do not have zoning regulations. Where towns have zoning, they can regulate issues such as hours of operation, truck routes and speeds, covering of truck beds, mine depth, and road repair liability through conditional use permits. Noise mitigation during mining, processing, and trucking is also usually controlled by local ordinances (Wisconsin Department of Natural Resources, 2012).
- Reclamation: Mines in Wisconsin must abide by NR-135, the nonmetallic mining reclamation requirement. These regulations are administered by the counties with WDNR oversight. Mining companies must submit a detailed plan for site reclamation before construction is begun. A provision is in place that requires a bond to the county to cover the cost of reclamation should the mining company go out of business (Wisconsin Department of Natural Resources, 2012).

Principal Frac Sand/Proppant Producing Companies

Some of the largest U.S. companies engaged in frac sand mining and processing are Texas Silica in Brady, Texas; Preferred Sands, LLC, in Radnor, Pennsylvania; Unimin Corporation in New Caanan, Connecticut; U.S. Silica, headquartered in Frederick, Maryland (Maslowski, 2012); and Fairmount Minerals and their subsidiaries (Tom Dolley, U.S. Geological Survey, written commun., September 29, 2014). Many additional companies are involved in the mining and processing of frac sand, are producers of resin-coated sand, or are manufacturing synthetic proppants in North America. With such a dynamically evolving market, the list of companies with descriptions below is not meant to be 100 percent complete but includes many operators that have been highlighted in the recently published literature and in Internet references obtained by the authors. There is no intent to exclude or to preferentially include any particular company. The goal is to present a relatively representative list of frac sand and proppant industry operators, the source units they are mining, and the locations of principal frac sand mining and processing activities.

- American Silica has invested in a frac sand processing plant near Batesville, Arkansas (Franco, 2013).
- Arkhola Sand and Gravel Company is dredging modern Arkansas River sands for use as frac sand in Sebastian County, Arkansas (Encyclopedia of Arkansas, 2014).
- Atlas Resin Proppants, LLC, produces resin-coated sand in Wisconsin (Beckwith, 2011).
- Badger Mining Corp. supplies the oil and gas industry with “Northern White” sand from two production facilities in Wisconsin where sand from the Wonewoc Formation and the St. Peter Sandstone is processed (Badger Mining Corp, 2014).
- Cadre Proppants operates near Brady, Texas (Zdunczyk, 2014), producing 800,000 tons per year of premium Hickory Sandstone Member products at API/ISO 16/30, 20/40, and 30/50 mesh (Tucker, 2013).

- Canadian Sand and Proppants operates the Sumner Mine and processing plant in Barron County, Wisconsin (Wisconsin Watch.org, 2013).
- Carbo Ceramics manufactures ceramic proppants in Toomsboro, Georgia, and in New Iberia, Louisiana (Beckwith, 2011).
- Chieftain operates the Dovre Mine and processing plant in Barron County, Wisconsin, and has interests in Arkansas (Wisconsin Watch.org, 2013). The company's plants in New Auburn, Wisconsin, and Garland City, Arkansas, manufacture ISO/API grade 20/40, 30/50, 40/70 proppants, as well as 100-mesh frac sand proppants (Chieftain Sand, 2014).
- CRS Proppants produce resin-coated sand in Louisiana (Beckwith, 2011).
- Delta Company is open-pit mining Quaternary sands adjacent to the Arkansas River in eastern Pulaski County, Arkansas, for use as frac sand (Encyclopedia of Arkansas, 2014).
- EOG Resources, Inc., a Houston-based oil and gas producer, operates the Cooks Valley Mine and the Howard Mine in Chippewa County and the Arland Mine in Barron County, Wisconsin. Its mines in Wisconsin supply frac sand to its Eagle Ford Formation plays, which saves the company an estimated $1 to $2 million per well (Snyder, 2013). EOG operates a plant near Chippewa Falls, and the "DS" Mine near Colfax, Wisconsin, that extracts sand from the upper part of the Wonewoc Formation after removing overburden consisting of unconsolidated sediment and sandstone of the Tunnel City Group (Runkel and Steenberg, 2012).
- Erna Frac Sand, L.C., produces a 98-percent monocrystalline quartz sand ("Erna Brite") with shape requirements that exceed API requirements from the Upper Cambrian Hickory Sandstone Member of the Riley Formation in Mason County, central Texas (Erna Frac Sand, 2014).
- Fairmount Minerals, Ltd., Technisand, Inc., Premium Resin Coated Sand is a subsidiary of Fairmount Minerals/Santrol located in Roff, Oklahoma; Wedron and Troy Grove, Illinois; and in Bridgman, Michigan (Fairmount Minerals, 2014b). In 2013, Fairmount Minerals acquired Frac Tec (proppant specialists) with operations near Brady, Texas; Oakdale, Wisconsin; and in Missouri (Zdunczyk, 2014). Fairmount Minerals was reported as operating underground frac sand mines in the Van Oser Member of the Jordan Formation in Maiden Rock and Bay City, Pierce County, Wisconsin (Runkel and Steenberg, 2012).
- FTS International/Proppant Specialists operates the Arcadia Mine and processing plant in Trempealeau County, Wisconsin (Wisconsin Watch.org, 2013; Trempealeau County, 2014). This company was purchased by Fairmount Minerals in 2013 (Tom Dolley, U.S. Geological Survey, written commun., September 29, 2014).
- Great Northern Sand operates mines and dry plants near Dovre, in Barron County, Wisconsin (Urban, 2014).
- Great Plains Sands sold its interest in the Great Plains Sands Mine and processing plant near Jordan in Scott County, Minnesota, to Fairmount Minerals, Ltd., of Ohio (Belle Plaine Herald, 2013).
- Hi Crush Proppants operates mines and processing plants at Oakdale and Wyeville in Monroe County, Wisconsin (Wisconsin Watch.org, 2013). The company's frac sand reserves are "Northern White," mainly from Wisconsin and limited portions of the upper Midwest (Hi Crush Proppants, 2013).
- Hi-Crush Partners, L.P., that is 50 percent owned by Hi Crush Proppants (Tom Dolley, U.S. Geological Survey, written commun., September 29, 2014), is a frac sand producer in Wisconsin (Wisconsin Watch.org, 2013). The company's reserves consist of "Northern White" sand, predominantly from Wisconsin and limited portions of the upper Midwest (Hi-Crush Partners, 2013).
- Manley Bros. of Indiana, Inc., operates in Dome, Illinois, where it mines frac sand from the St. Peter Sandstone near Troy Grove on the La Salle anticline (Manley Brothers, 2014).
- Midwest Frac, LLC, is involved in the operation of the Arland Mine in Barron County, Wisconsin (Wisconsin Watch.org, 2013).
- Minnesota Frac Sand, LLC, is developing the Schneider Mine near Arcadia in Trempealeau County, Wisconsin (Wisconsin Watch.org, 2013; Trempealeau County, 2014).
- Momentive (formerly Hexion) produces resin-coated proppants at their facility in Cleburne, Texas (Beckwith, 2011).
- Northern Frac Proppants has drilled on over 3,000 acres of land at three locations in western Wisconsin, producing "high-quality Northern White sand" at processing plants in Jackson County (Northern Frac Proppants, 2014).
- Northern Frac Sand operates the Hansen Mine in Wood County, Wisconsin (Wisconsin Watch.org, 2013).
- Patriot Proppants produces resin-coated proppants at Shreveport, Louisiana, and at Guion, Arkansas (Beckwith, 2011).

- Pattison Sand Co., LLC, operates surface and underground frac sand mines from the St. Peter Sandstone in Clayton, Iowa (Pattison Sand, 2014), and has interest in operating the Bridgeport Mine and a processing plant in Crawford County, Wisconsin (Wiedemann, 2014).

- Preferred Sands, LLC, owned by Preferred Proppants (Tom Dolley, U.S. Geological Survey, written commun., September 09, 2014), produces frac sand from the St. Peter Sandstone in Washington County, Minnesota; from the St. Peter Sandstone and Jordan Formation in Trempealeau and Chippewa Counties, Wisconsin; and from a high-quality white sand near Flin Flon in Manitoba, Canada. They also produce resin-coated sand from the Bidahochi Formation near Sanders, Arizona (Preferred Sands, 2012).

- Preferred Sands of Genoa, LLC, also owned by Preferred Proppants (Tom Dolley, U.S. Geological Survey, written commun., September 29, 2014), produces silica sand and resin-coated proppants from sands dredged from the Loup River near Genoa, Nebraska (Interstates, 2012).

- Premier Sand near Brady, Texas, supplies frac sand to the Permian Basin. Premier Sand is the name used by Pioneer Resources after it acquired Carmeuse Silica Sand in Brady (Zdunczyk, 2014).

- Proppants Barron is involved in the operation of the Dovre Mine in Barron County, Wisconsin (Wisconsin Watch.org, 2013).

- Saint-Gobain U.S. manufactures ceramic proppants (Beckwith, 2011).

- Santrol Proppants is a subsidiary of Fairmount Minerals that produces resin-coated proppants at facilities in Roff, Oklahoma (Beckwith, 2011), in Wedron and Troy Grove, Illinois, in Bridgman, Michigan, and in Fresno, Texas; it produces frac sand from the Hickory Sandstone Member in Voca, Texas, and “Northern White” from their mines in the St. Peter Sandstone (Fairmount Minerals, 2014a).

- Sargent Sand Co., located in Ludington, Michigan, is mining and processing frac sand from Quaternary dune deposits on the eastern shore of Lake Michigan (Sargent Sand, 2014).

- Short Mountain Silica Co., located near Mooresburg, Tennessee, began in 2012 to offer 30/50 and 40/70 sand for frac sand applications (Short Mountain Silica, 2014). This silica sand is mined from the Silurian Clinch Sandstone, a quartz arenite (orthoquartzite) that forms Short Mountain, a part of the larger Clinch Mountain system (Zdunczyk, 1992).

- Sierra Frac operates the Patzner Sand Pit at Arcadia in Trempealeau County, Wisconsin (Wisconsin Watch.org, 2013).

- Sioux Creek Silica, a subsidiary of Global Proppant Supply, LLC, has received a permit to build a 981-acre frac sand mine site, drying and transload facility, and a 4.7-mi conveyor system connecting the sites in Barron County, Wisconsin, that will operate in the towns of Dovre and Sioux Creek (Urban, 2014).

- Southern Precision Sands produces resin-coated proppant in Alabama (Beckwith, 2011).

- Spartan Sands, LLC, operates the Blair Mine in Trempealeau County, Wisconsin (Wisconsin Watch.org, 2013).

- Summit Proppants, Inc., produces high-purity monocrystalline quartz sands sold as 20/40, 30/50, and 40/70 frac sand from a mine in the Lamotte Sandstone in Ste. Genevieve County, Missouri, where it is stratigraphically equivalent to the Mount Simon Sandstone. Summit states that the sands have exceptional sphericity and roundness and meet or exceed all ISO 113505-2AP 19 C Standards (Summit Proppants, 2013).

- Superior Silica Sands, LLC, operates the Arland Mine in Barron County, Wisconsin (Wisconsin Watch.org, 2013). The company reports that it produces frac sand at processing plants in New Auburn and Clinton, Wisconsin, and that it mines and processes a “Native Texas” frac sand and processes “Northern White” in Kosse, Texas (Superior Silica Sands, 2014).

- Texas Silica, LLC (or Texas Silicate Distributors, LLC), produces “Brady” or “Brown” frac sand from the Upper Cambrian Hickory Sandstone Member of the Riley Formation near Brady, in central Texas. The sand mined in the Voca area is coarser than the “Northern White,” having sizes from 8/16, 12/20, and 16/30 that are suitable for wells with closure pressures of less than 4,500 psi (Texas Silica, 2014a). Sand mined about 10 mi (16 km) northwest of Fredonia has a higher count of 20/40 and 30/50 monocrystalline sand and has a higher crush resistance than the sand from other Brady sites (Texas Silica, 2014b). Near Erna, Texas, they also produce “Erna Brite” frac sand that is described as much like the “Northern White” in quality.

- U.S. Silica Co. mines frac sand from the St. Peter Sandstone in Ottawa, Illinois; and “frac-capable” sand from the St. Peter in Pacific, Missouri; “frac-capable” sand in Sparta, Wisconsin; “frac-capable” sand from the Sylvania Sandstone in Rockwood, Michigan; “frac-capable” sand from the Oil Creek Sandstone in Mill Creek, Oklahoma; and frac sand from the “Sandhills” area southwest of Columbia, South Carolina;

and it produces resin-coated sand in Rochelle, Illinois (U.S. Silica, 2014c). U.S. Silica also has interests in Arkansas.

- Unimin Corp. mines and produces hydraulic fracturing sands, pre-cured resin-coated, and curable resin-coated proppants for a large portion of the market; Unimin has frac sand mines and processing plants in Guion, Arkansas; Ottawa, Kasota North, and Kasota South, Minnesota; Portage and Tunnel City, Wisconsin; Oregon, Troy Grove, and Utica, Illinois; Pevely, Missouri; and Cleburne and Voca, Texas. Unimin runs one of the few underground mine operations in Arkansas. Unimin has additional silica sand operations and facilities in Tennessee, Oklahoma, Louisiana, Georgia, South Carolina, North Carolina, Virginia, New Jersey, Idaho, and in Coahuila, Nuevo Leon, Tlaxcala, and Vera Cruz, Mexico (Unimin, 2014).
- Wisconsin Industrial Sand Co. produces frac sand from the Jordan Formation at their underground mine in Maiden Rock, Wisconsin (Jones, 2006).

Frac Sand Consumption History in the United States

Contributed by Donald I. Bleiwas

Source Supplies of Frac Sand

In 2014, approximately 70 percent of the silica sand used for proppant was mined in the Great Lakes Region, which included Illinois, Minnesota, Michigan, and Wisconsin. Wisconsin and, to a lesser extent, Illinois and Minnesota are the primary producers of the Nation's highest quality frac sand. Wisconsin accounts for nearly one-half of all the frac sand capacity in the United States owing to its premium sand deposits, railway infrastructure, and long-term presence in the industry. Most of the balance of frac sand production originates from Arizona, Arkansas, Nebraska, Oklahoma, and Texas (U.S. Geological Survey, 1991–2014; Pioneer, 2012; Fracmapper, 2013; PacWest, 2014a).

Silica Sand Consumption

From 1990 through 2012, a total of approximately 654 million metric tons (Mt) of industrial silica sand, valued at 20.3 billion dollars adjusted to average 2013 dollars (avg. 2013) free on board (FOB) plant, were sold and used in the United States (U.S. Geological Survey, 1991–2014)[1]. For the period 1990 to 2012, about 119 Mt, or 18 percent of that tonnage were used as silica-sand proppant in hydraulically fractured gas and oil wells with an estimated total value of about 6.6 billion dollars (avg. 2013) (U.S. Geological Survey, 1991–2014).

Silica sand has the highest consumption tonnage and total combined value of all natural and manufactured proppants consumed in the petroleum industry because of its relatively low unit cost, ready availability, and overall performance. Estimates vary, but shares by weight in the 2011 to 2013 period represented approximately 80–90 percent for frac sand, with the balance split roughly equal between resin-coated sand (RCS) and ceramics (U.S. Geological Survey, 1991–2014; Mawet and others, 2012; Hughes, 2013; Thomas Curan, Analyst, FBR Capital Markets and Company, New York, N.Y., oral commun., August 12, 2014). In 2013, frac sand represented nearly 85 percent of the North American proppant

[1]Dollar values were adjusted to average 2013 dollars using the U.S. Department of Labor's U.S. Bureau of Labor Statistics Consumer Price Index (U.S. Department of Labor, 2014).

market by weight, was used exclusively in almost 75 percent of horizontal wells, and was a component of about 95 percent of all wells fracked. Resin-coated sand and manufactured ceramic proppants composed the balance (PacWest, 2014a,b). The estimated amount of frac sand consumed in major U.S. shale plays for the last 3 quarters of 2013 and 1st quarter of 2014 is shown in table 2. The top three frac-sand consuming units or basins in the United States and the amount used are, in descending order of estimated consumption, the Eagle Ford and Woodbine Formations in the East Texas Basin (9.5 Mt), Appalachia (6.8 Mt), and the Permian Basin (5.3 Mt) (Pacwest, 2014b).

In 2013, frac sand proppants composed about a 57-percent share of the total wholesale proppant market value, ceramic proppants had a 26-percent share, and resin-coated sand had about a 17-percent share. The percentage share of frac sand was expected to increase to nearly 65 percent in 2014 (PacWest, 2014b).

Pricing of Frac Sand

As a result of high demand and tight supply, the price of frac sand increased to a national average of about $63 (avg. 2013) per ton FOB plant from about $50 (avg. 2013) per ton FOB plant in 1990. The major factors that determine the price for frac sand include (1) its strength, which is based on its SiO_2 content; (2) its sphericity; (3) its grain size and uniformity; and (4) its overall purity. In general, the relatively clean, coarse, and silica-rich high-strength “white” sands mined in Illinois, Minnesota, and Wisconsin bring the highest prices, averaging about $55 per ton FOB plant. The coarser fractions bring premium prices of approximately $70 per ton FOB because of their higher conductivity, especially for recovering oil. In 2013, white sand represented about 65 percent, by weight, of the untreated silica sand used for fracking (PacWest, 2014b). In 2013, brown sand represented about 35 percent, by weight, of the untreated silica sand used for fracking (PacWest, 2014b). Finer grain size and less spherical brown sands, mined in Arkansas and Texas, are priced at about $65 per ton FOB plant. On average, they cost more to mine than those in the Great Lakes region, but they experience significantly lower transportation costs because of the shorter distance to well sites. They are generally considered of lesser quality because of lower silica content and lower sphericity with commensurate lower strength and lower conductivity. Their relatively low resistance to pressure generally limits their use to a fracking depth of about 8,000 feet (Lyle, 2011; CARBO Ceramics, 2012; PacWest, 2014b; U.S. Geological Survey, 2014).

In most cases, rail is the primary form of transportation to get sand from the mine to the transfer point closest to the well site and represents the highest post-mine cost. Depending on the modes of transport, distances traveled, and number of transfer points, the cost of white silica frac sand proppant may reach $170 per ton by the time it arrives at the well site (PacWest, 2014b).

Growth in Frac Sand Consumption and Value

A time series chart (fig. 26) shows (1) the number of metric tons of silica sand proppant sold or used for each of the years during the period 1990 through 2012 (the most recent year for which statistical data is available) as reported by the USGS; (2) annual FOB plant values of frac sand termed “sold or used” (because some are inventories and stockpiles) for each of the years during the period 1990 through 2012, as reported by the USGS, expressed in average 2013 dollars; and (3) the average number of active horizontal drilling rigs per week per year, as reported by Baker Hughes, Inc., for the period 1991 (the first year that statistical data were available) through 2012 (Baker Hughes, Inc., 2014). Frac sand values are FOB plant and do not account for the value added to some sands that are processed further on site, specifically RCS. From 1990 to 2002, the demand for sand as a proppant was relatively level, averaging about 1.5 Mt per year or about 6 percent of the approximately 25 Mt of industrial sand sold or used annually during the period. The average price per ton of frac sand during this period was about $50 per ton FOB plant in average 2013 dollars. From 1990 to 2002, the number of onshore horizontal drilling rigs operating on a weekly basis in the United States averaged about 60 units or 7 percent of active onshore wells. Vertical and directional (angled or deviated drilling, but not horizontal) drilling rigs dominated U.S. onshore drilling activity over the time period with about 73 percent and 20 percent shares, respectively (Baker Hughes, Inc., 2014).

In 2003, nearly 2.2 Mt of sand was sold or used for fracking, a 45-percent increase over the previous year. The rapid growth in the demand for frac sand at this time was a direct result of the petroleum industry’s start of aggressive horizontal drilling and hydraulic fracturing programs in unconventional oil and gas targets contained in tight sedimentary formations. In 2009, the global recession and lower petroleum prices were reflected by a decrease in the number of active drilling rigs and a slowdown in the growth rate of frac sand consumption. By 2012, oil petroleum prices had recovered and the rate of growth in frac sand demand accelerated. In 2012, there was an average of approximately 1,150 horizontal rotary drilling rigs in the United States operating per week, which represented nearly 60 percent of the total number of active drilling rigs. At the same time, the number of vertical and directional active drilling rigs represented 29 percent and 11 percent shares, respectively (Baker Hughes, Inc., 2014). The compound annual growth rate (CAGR) for frac sand sold or used for the years 2003 through 2012 was nearly 32 percent.

The amount of silica sand sold or used for other uses, such as glassmaking and foundry applications, during the same period dropped by nearly 5 Mt for a negative compound annual growth rate of 2.2 percent for the time period. Nearly 71 percent of the total tonnage of frac sand sold and used over the 13-year period occurred during the period 2008–12 and was valued at 4.7 billion dollars (avg. 2013) FOB and reflects the U.S. petroleum industry’s increase in drilling in unconventional oil and gas targets in tight formations. The surge in frac sand consumption relative to the number of active horizontal drilling rigs has increased substantially over the last several years. This results from numerous factors that include (1) application of advanced technologies such as (a) multistage and higher density hydraulic fracturing per well, which increased from an average of about 3.4 hydraulic fracturing stages in 2008 to over 13 at the beginning of 2012. In 2014, wells with 30 stages were not uncommon, and some wells have as many as 50 stages; (b) methods that result in more extensive fracturing in bedrock; and (c) reservoir stimulation of older wells by hydraulic fracturing; (2) improved efficiencies by drilling multiple holes from one site with closer spacing; and (3) refreshing of previously fracked wells by re-fracking (Schaefer, 2009; McDivitt, 2013; Nangia, 2013; Tucker, 2013; CBC News, 2013; Helman, 2014; Schlumberger, 2014). These advances have increased the average proppant consumption per well. For example, in 2008, the average amount of proppant, which was nearly all sand, used per horizontal well was approximately 900 tons (t) for a 1,500-m well. In 2010, the average amount of sand used was closer to 2,300 t for a well completed on a 3,000-m length measured horizontally. In 2014, an average horizontal well consumed from 4,100 to nearly 5,000 t of proppant of which over 90 percent, by weight, was sand, equivalent to 40 to 50, 100-short-ton capacity train-car loads. In a few recent cases, wells required about 9,000 t of sand (Cadre Proppants, 2013; Fielden, 2013; Rock Products, 2014f). Also, a well may be re-fracked multiple times over its life to increase production or refresh the well (Streetwise Reports, 2013; Tate, 2014). For the purpose of comparison, from 2011 through mid-2014, the amount of proppant required for fracking a vertical drill hole, nearly all of which was sand, remained essentially level, at about 230 t per well (Down Hole Trader, 2014; Geiver, 2014; PacWest, 2014b).

The average amount of proppant used per unit distance for horizontal holes is expected to continue to climb with improved fracturing technologies, closer-spaced and increased number of stages per drill hole, and refreshing of previously developed wells.

Table 2. Estimated frac sand consumption among major U.S. unconventional oil and gas shale plays and (or) basins. These estimates are provided by PacWest (2014b) and are subject to revision.

Major producing and active exploration and development shale plays/basins for unconventional oil and gas	State(s) or region with activity	Million metric tons of frac sand consumed (rounded to two significant figures)[1]	Percentage share of total frac sand consumed in listed plays/basins[1]	Estimated share of frac sand to total proppants consumed (percent)[1]
Eagle Ford-Woodbine play	Texas	9.5	30	95
Appalachia (Appalachian Basin) (includes Marcellus and Utica Shales)	Northeastern U.S.	6.8	22	100
Permian Basin	New Mexico, Texas	5.3	17	90
Bakken play	Montana, North Dakota	2.2	7.0	69
Anadarko Basin	Kansas, Oklahoma, Texas	2.1	6.6	91
Denver-Julesburg Basin	Colorado, Kansas and Nebraska; Wyoming; and South Dakota	1.3	4.2	98
Haynesville-Brown Dense play	Louisiana, Texas	1.3	4.1	93
Barnett play	Texas	0.90	2.9	99
Fayetteville play	Arkansas	0.45	1.5	100
Uinta Basin	Utah	0.32	1.0	89
Piceance Basin	Colorado	0.26	0.84	96
Other	Various	0.83	2.7	91
Total	—	**31.26**	**99.84**[2]	

[1]Tonnage and percentage estimates based on data for last 3 quarters of 2013 and 1st quarter of 2014 by PacWest (2014b).

[2]Numbers do not add up to 100 percent due to independent rounding.

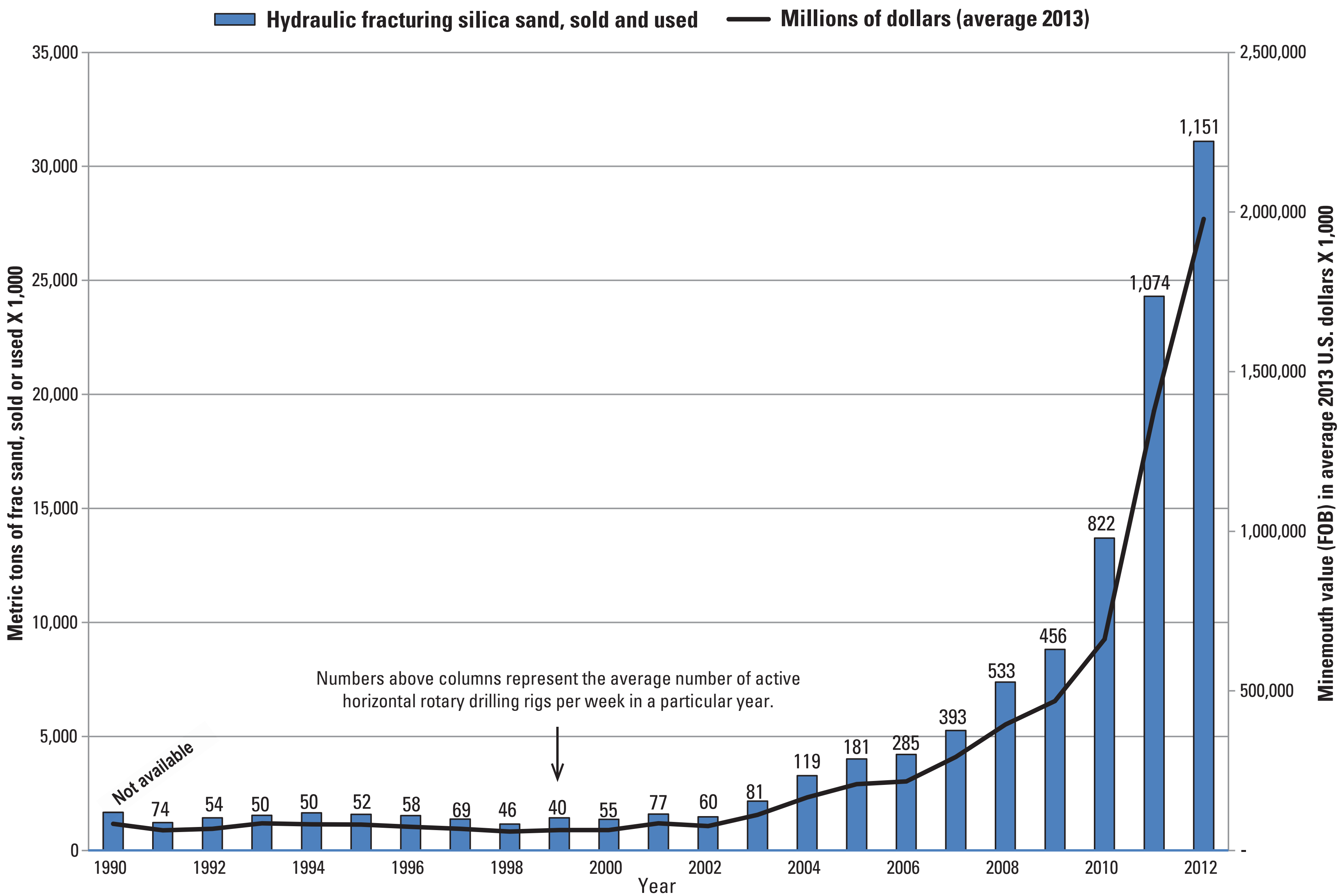

Figure 26. Average weekly horizontal drill rig count per year, frac sand sales, and free on board (FOB) mine values (U.S. Geological Survey, 1991–2014; Baker Hughes, Inc., 2014).

Outlook for U.S. Frac Sand Market

Barring factors that could negatively affect frac sand demand, such as major technological breakthroughs and (or) a significant drop in oil and gas prices that are considered to be long term by the petroleum industry, frac sand will continue to represent the largest tonnage used among proppants and the highest total value for fracking until at least the year 2020, based primarily on (1) its satisfactory performance in most applications, (2) its availability, and (3) its lower price compared to alternative materials. The average amount of proppant used per unit distance for horizontal holes is expected to continue to climb with improved fracturing technologies, closer-spaced stages, and increased number of stages per drill hole. Demand for proppant will also increase as more previously drilled wells are refreshed, established ones further exploited, and new oil and gas fields are developed. Wisconsin will retain its position as the largest supplier among States that produce frac sand.

Current Challenges to the Frac Sand Industry

The principal economic challenges to the frac sand industry include market conditions surrounding the continued demand for the product; proximity of source to end user and other factors impacting transportation costs; local and national regulations on environmental impacts of mining, transport, and application of frac sand; and internal and external competition for the proppant market. Cultural challenges include public response to cost-benefit analyses of mining within State and local jurisdictions (Power and Power, 2013). Although the supply of frac sand is not yet under threat of depletion, States and sand suppliers are engaging in the search to evaluate formations that could become future sources of frac sand or be modified by resin coating for use as proppants.

According to Zdunczyk (2007), the majority of the optimal frac sand sources in the United States are known; therefore, he recommends that exploration efforts should focus on the known units and their stratigraphic equivalents. As the principal compositional requirement of frac sand is a high silica content, such sand deposits are well known because they have been mined for decades for glass-making, metallurgical, water-filtration, sports and recreation, and building product uses (Geology, 2013). Among the high-silica sands, the additional unique API specifications make frac sand especially uncommon.

Hi-Crush Partners, L.P., a Wisconsin producer of frac sand, notes these constraints to increasing raw frac sand production on an industry-wide basis (Rock Products, 2014e):

- The difficulty of finding frac sand reserves that meet API specifications.
- The difficulty of securing contiguous frac sand reserves large enough to justify the capital investment required to develop a processing facility.
- The challenges of identifying reserves with the above characteristics that either are located in close proximity to oil and natural gas reservoirs or have rail access needed for low-cost transportation to major shale basins.
- The hurdles to securing mining, production, water, air, refuse and other federal, state and local operating permits from the proper authorities.
- Local opposition to development of facilities, especially those that require the use of on-road transportation, including moratoria on raw frac sand facilities in multiple counties in Wisconsin that hold potential sand reserves.

- The long lead time required to design and construct sand processing facilities that can efficiently process large quantities of high quality frac sand.

As part of the continued search for additional sources of frac sand, companies are considering mining less-than-ideal deposits. A "multiple markets approach" has been proposed for deposits in North Dakota, for example, that contain a wide range of grain sizes, so that the considerable volumes of sand in the deposit that do not meet API requirements are economically delivered to other markets (Anderson, 2011).

Global Outlook for Frac Sand and Alternative Proppants

As unconventional oil and gas production is expected to play a major role in meeting the global demand for energy, a greater demand for frac sand and manufactured proppants is anticipated (Snyder, 2013). Projections of growth in the energy market have resulted in the following predictions of market demand for frac sand in North America and the world.

According to The Freedonia Group, a Cleveland-based market research firm, the North American frac sand market is estimated to increase as much as 8.9 percent each year through 2016 to 34.4 million metric tons, valued at $2.2 billion. They project that, by 2016, the United States will continue to lead the world in frac sand consumption using 75 percent of the market supply; Canada will be second in volume consuming 8 percent of the market supply (Rock Products, 2014b).

On the broader global front, The Freedonia Group reports that Russia and China are developing frac sand markets with their expansion of hydraulic fracturing; however, they tend to rely more on ceramic proppants, curtailing their participation in the frac sand market (Rock Products, 2014b).

Recent downturns in oil and gas prices are beginning to have an impact on petroleum production worldwide. These trends are expected to influence the future health of the frac sand industry.

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Glossary

frac sand A naturally occurring, highly pure silica sand that is used as a proppant during hydraulic fracturing of oil and gas wells for the purpose of maximizing production from tight, unconventional reservoirs.

frack (ed, ing) Hydraulically fractured (fracturing)

hydrofracturing Hydraulic fracturing

proppant A granular material that is added to the fracking fluid to prop open the fractured formation to promote the economic flow (conductivity) of hydrocarbons during the well's productive life.

Appendix 1. Explanation of Map Units Shown on Plate 1 and in Map Figures.

Sources of Data

The map units shown on plate 1 and in the map figures of this report are composites of selected units derived from individual State-scale geologic maps. These individual State maps, which are available online at http://mrdata.usgs.gov/geology/state/, are being modified, updated, and combined by John Horton, Carma San Juan, and Doug Stoeser, USGS, into a nationwide dataset, State Geology Map Compilation (SGMC) (unpub. data), which is planned as a USGS data series for release in the near future. Rather than reassemble each of the State maps, the authors of this report have relied on the SGMC in its current state of completion.

Modification of the SGMC's extent of the St. Peter Sandstone by the removal of the Prairie du Chien Group in Iowa was provided by Bob McKay of Iowa Geological and Water Survey, Iowa Department of Natural Resources, in the fall of 2013 (Robert McKay, Iowa Geological and Water Survey, unpub. data).

Compilation of Map Units

Due to the small scale at which the reference State maps were compiled, most of the map units in this study contain not only the unit of interest but also associated geologic units that have no frac sand potential. Thus, the areas identified as containing frac sand source units on our maps are frequently overrepresented. Although, in many cases, more detailed (larger scale) mapping of the units of interest has occurred, such maps are not consistently available in digital format for most States, let alone the entire country.

The following is a complete list of the units that are featured in the geologic map figures, plate 1, and the accompanying GIS dataset. These units are grouped into three main categories: units producing frac sand, units producing resin-coated sand, and units with lmited potential to produce frac sand. These map units are arranged in the order in which they are discussed in the accompanying text. Each map unit presented here (in all capital letters) is a compilation of all the geologic units that might contain that named frac sand-bearing unit (see the accompanying metadata), as well as, in some cases, the associated non-frac sand units that are not differentiated from it in the source data. Frac sand units of interest are discussed generally and then by State (indicated by the two-letter post office abbreviation), and the States are listed alphabetically. Where names of units vary geographically (that is, a unit may be referred to as a sandstone on one map and a formation on another), the name used on the original map is the one listed. Except where noted, the map unit contains the named formation in addition to associated formations. The geologic age (system or series) follows the name of the map unit. The specific color assigned to the unit (as depicted in the ArcGIS dataset) is named in parentheses. Map symbols for each individual unit on the SGMC-compiled State maps are included in brackets. This SGMC field for "Orig_Label" may vary by State and uses plain letters instead of the official USGS geologic age symbols (that is, they may use TR or @ instead of Ꞧ, or C or _ or CA or [instead of Ꞓ, or P or IP or PA instead of ℙ).

PRODUCING FRAC SAND UNITS

ST. PETER SANDSTONE (AND ASSOCIATES). MIDDLE AND UPPER ORDOVICIAN. (MALACHITE GREEN)

Note that this unit includes all of the Ancell Group in IL, all of the Middle Ordovician in MN, all of the Ordovician in WI, but only the St. Peter Sandstone in IA.

In Iowa, the units containing St. Peter Sandstone were provided by Bob McKay of the Iowa Geological and Water Survey (unpub. data). The maps McKay provided ostensibly separate the St. Peter Sandstone from the rest of the Ancell and Prairie du Chien Groups.

AR Contains (combined) St. Peter Sandstone and Everton Formation (Middle Ordovician) [Ose]. [Interestingly, all of the silica mines (as determined from the USGS Minerals Resource Data System (MRDS) database) are south of this unit.]

IA St. Peter Sandstone [Osp]. These data were obtained by Bob McKay at Iowa Survey to eliminate all non-St. Peter Sandstone (mostly Prairie du Chien) in the Ordovician from the State map (same as SGMC).

IL Ordovician units. Includes all of Ancell Group [Oa].

MI There is no St. Peter Sandstone mapped at the surface on the State map, but the St. Peter Sandstone is extensive and thick in the subsurface.

MN Middle and Upper Ordovician (no more-detailed mapping exists at State-scale) [Omu].
MO Ordovician. Contains (combined) St. Peter Sandstone and Everton Formation [Ospe].
WI Ordovician. Includes all of Ancell Group [Oa].

CAMBRIAN, UNDIVIDED. CAMBRIAN. (LILAC DUST)

This unit combines all undifferentiated or undivided Cambrian units in IL, MN, and WI. The unit may include the Jordan, Wonewoc/Munising, and Mount Simon Formations, and other units.

IL Cambrian System [C] contains Jordan, Wonewoc, and Mount Simon Formations, and everything in between.
MN Middle and Upper Cambrian, undivided [Cmu] contains Jordan, Wonewoc, and Mount Simon Formations, and everything in between.
WI Cambrian, undivided [Cu] contains Jordan, Wonewoc, and Mount Simon Formations, and everything in between.

JORDAN FORMATION (AND ASSOCIATES). UPPER CAMBRIAN AND LOWER ORDOVICIAN. (MARS RED)

IA Contains Jordan, St. Lawrence, and Lone Rock Formations [Cj]. Only in IA.
MI Jordan Sandstone Member is a unit within the Trempealeau Formation [Ct].

WONEWOC FORMATION/MUNISING FORMATION (WONEWOC FORMATION AND ASSOCIATES). UPPER CAMBRIAN. (ROSE QUARTZ)

IA Mapped as Wonewoc Formation [Cw] in IA on SGMC. Not combined with anything else.
MI Munising Formation [Cm] is equivalent to Wonewoc Formation. Munising includes (bottom to top): basal conglomerate, Chapel Rock Member, Miners Castle Member (Heinrich, 2001). The 40 to 60 ft thick Chapel Rock Member has potential for glass sand.

MOUNT SIMON FORMATION/LAMOTTE SANDSTONE. UPPER CAMBRIAN. (CANTELOUPE)

IA Mapped as Mount Simon Formation [Cm] in IA on SGMC. Not combined with anything else.
MI None mapped in MI.
MO Mapped as Lamotte Sandstone [Clm].

HICKORY SANDSTONE MEMBER OF THE RILEY FORMATION. UPPER CAMBRIAN. (CHRYSOPRASE)

TX Hickory Sandstone Member of the Riley Formation [Ch]. Mapped subdivided from the Riley Formation.

OIL CREEK FORMATION (AND ASSOCIATES). MIDDLE ORDOVICIAN. (FUSCHIA PINK)

OK Contains both Oil Creek and Joins Formations [Ooj]. Frac sand is only in the lower member of the Oil Creek.

PRODUCING SANDS FOR RESIN-COATED PROPPANT

SPARTA SAND. EOCENE. (50% GRAY)

TX Sparta Sand [Es].
LA Sparta Formation [Ecs].

CATAHOULA FORMATION. OLIGOCENE. (APATITE BLUE)

Note that the age of this unit is variable: it is classified as Oligocene in LA and TX and Miocene in MS.

LA Oligocene Catahoula Formation [Oc] and [Oc-l].
MS Miocene Catahoula Formation [Mc].
TX Oligocene Catahoula Formation [Oc] and Catahoula Formation and Frio Clay, undivided [Ocf].

BIDAHOCHI FORMATION (AND ASSOCIATES). PLIOCENE. (ELECTRON GOLD)

AZ Mapped as Tbs (Richard and others, 2000) and as Tsy on State map (Wilson and others, 1969). Any bodies of Tsy south of the area shown on the older map as Tbs were removed, following the distribution of Love (1989). [Tsy].

NM The unit almost certainly extends into western NM, but the units cannot be reconciled with the NM State map.

LOUP RIVER SAND. QUATERNARY. (SEE GENOA, NEBRASKA, ON MAP; GEOLOGIC UNITS NOT SHOWN; COORDINATES ARE FOR A POINT ABOUT MIDWAY ALONG CANAL.)

NE Sand is along canal, immediately north of the river and west of the Gaging Station (at the power plant), about 5 mi southwest of Genoa, in eastern Nance County, about 5 mi from county line. Coordinates for near center of canal are 41.4017 -97.8083 (WGS84). No Quaternary units are mapped on Nebraska's State map. Bedrock is mapped as Tertiary Ogallala Formation on the north, Cretaceous Niobrara Formation to the south.

POTENTIAL FRAC SAND SOURCE UNITS

ANTIETAM FORMATION (AND ASSOCIATES). LOWER CAMBRIAN. (BURNT UMBER)

Antietam Formation is a unit at the top of the Chilhowee Group. It is assumed that Antietam is present everywhere Chilhowee is mapped as undifferentiated, unless a unit is named that does not contain Antietam (such as the Proterozoic units).

AL Chilhowee Group, undifferentiated [Cch].

GA Chilhowee Formation [Cch].

MD Chilhowee Group, Antietam Formation [Ca]. (Harpers Formation [hf], Loudoun Formation [lf], and Weverton Formation [wf] have been removed because they do not mention containing Antietam.)

NC Chilhowee Group, Upper Chilhowee [Ccu]. Removed all the Proterozoic only units which began with Chilhowee Group, Grandfather Mountain Formation: Zgma, Zgmg, Zgms, Zgmw, Zgmf, Zgmu. Removed Chilhowee Group; Lower Chilhowee [Ccl] because Antietam is in upper part of the group.

PA Antietam Formation [Ca], Antietam and Harpers Formations, undivided [Cah].

TN Includes Chilhowee Group (including Erwin Formation, Hesse Sandstone, Murray Shale, Nebo Sandstone, Nichols Shale, Cochran Conglomerate, Hampton Formation, and Unicoi Formation) [Cchi]. Deleted all the other Chilhowee Groups that mention a single formation that is not Antietam: Cochran Conglomerate [Cch], Hesse Sandstone [Che], Murray Shale [Cmu], Nebo Sandstone [Cnb].

VA Chilhowee Group [[ch].

WV Antietam Formation [Ca].

CHICKIES FORMATION (AND ASSOCIATES). CAMBRIAN. (AUTUNITE YELLOW)

PA Chickies is in the Upper Chilhowee Group [Cch], underlying the Antietam. Mapped as Chickies Formation. Only in Pennsylvania. Even though there are units mapped as "Chilhowee, undivided" in other States, they do not contain Chickies. (Also, mapped as Chickies Quartzite in PA and just into NJ [Lyttle and Epstein, 1987].)

CLINCH AND TUSCARORA SANDSTONES (AND ASSOCIATES). UPPER ORDOVICIAN TO LOWER SILURIAN. (ULTRAMARINE)

CLINCH SANDSTONE

TN Mapped by SGMC as Silurian Clinch [Sc] and Rockwood and Clinch Sandstone [Src].

KY Combined with Hancock, Rose Hill, and Clinch Formations [Shrc]. Sandstone is the first minor component of this undivided unit; sandstone is not a major lithology.

TUSCARORA SANDSTONE

Tuscarora Sandstone is within the Judy Gap Group in Pendleton County, WV (Chen, 1977), but Judy Gap is not shown or mentioned on any of the State maps.

MD Tuscarora Sandstone [St].
PA Tuscarora Formation [St].
VA Keefer, Rose Hill, and Tuscarora Formations [Skrt].
WV Contains McKenzie Formation, Clinton Group, and Tuscarora Sandstone, undivided [Sct]; and Tuscarora Sandstone [St].

ORISKANY SANDSTONE/GROUP (AND ASSOCIATES). MIDDLE LOWER DEVONIAN. (POINSETTIA RED)

The Oriskany Group includes the Esopus and Port Ewen Formations. Oriskany Group is divided into the Ridgeley Sandstone (upper) and Shriver Chert (lower). In NJ it is divided into Glenerie Formation, Shriver Chert and Ridgeley Sandstone. Old Port Formation is an overall unit containing Ridgeley Sandstone Member of Old Port Formation (Geolex http://ngmdb.usgs.gov/Geolex/Units/OldPort_3095.html).

MD Oriskany Group including Ridgeley Sandstone and Shriver Chert [Do].
NJ Oriskany Group, undivided [Do].
NY Oriskany Formation [Do].
PA Contains Onondaga and Old Port Formations, undivided [Doo]. Ridgeley Formation through Coeymans Formation, undivided [Drc]; Ridgeley Member of Old Port [Dor]. Only Ridgeley Member is of interest, so removed Shriver, Manadata, Corriganville, and New Creek Members of Old Port Formation, undivided [Dosn].
VA Ridgeley Sandstone and Helderberg and Cayugan Groups [DSu].
WV Oriskany Sandstone and Huntersville Chert [Do]; and Oriskany Sandstone and Helderberg Group, undivided [Dohl].

SYLVANIA SANDSTONE (AND ASSOCIATES). MIDDLE DEVONIAN. (SPRUCE GREEN)

Sylvania Sandstone is lowermost unit of Detroit River Group. Detroit River Group is mapped at extreme north of main body in MI and adjacent to the Sylvania in the southeast corner of MI. Sylvania has been mapped by itself in southeast MI. In northwest OH, it has not been differentiated from the Detroit River Group. Therefore, Detroit River Group is shown in OH, but not in MI.

MI Sylvania Sandstone [Ds].
OH Detroit River Group [Ddr] in northwest OH may possibly contain Sylvania.
Sylvania has not been described in the Detroit River Formation (combined with Columbus Limestone, undivided) [Ddc] in the middle of the State (Logan and Champaign Counties), therefore it is not included on this map.

BEREA SANDSTONE (AND ASSOCIATES). UPPER DEVONIAN. (MACAW GREEN)

TN and adjacent AL contain abundant Chattanooga Shale, but there is no mention of Berea in the SGMC or State of Alabama State map explanation. Therefore, Berea is not shown in these States.

KY Wildie, Nada, Halls Gap, Holtsclaw Siltstone, Cowbell, Nancy, Kenwood Siltstone, and New Providence Shale Members of Borden Formation; Sunbury Shale, Berea Sandstone, and Bedford Shale, undivided; Borden Formation locally includes Renfro Member in eastern Kentucky [Mdbb]; and Pennington Formation, Newman Limestone, Fort Payne Chert, Grainger Formation, Sunbury Shale, Berea Formation, and Bedford Shale, undivided; Pennington Formation locally includes sandstone tongue of Lee Formation [PADpg]—just two small polygons with this combination just north of State boundary intersection with both WV and TN.
MI Berea Sandstone [Db].
OH Berea Sandstone and Bedford Shale, undivided [Dbb]; and Sunbury Shale, Berea Sandstone and Bedford Shale, undivided [MDsb].
PA Berea Sandstone through Venango Formation, undivided [Dbv]; and Berea Sandstone through Riceville Formation, undivided [Dbr].

BUENA VISTA SANDSTONE MEMBER OF THE CUYAHOGA FORMATION (AND ASSOCIATES). LOWER MISSISSIPPIAN. (INDICOLITE GREEN)

Buena Vista Sandstone Member is an intermediary member of the Cuyahoga Formation. It is vastly overrepresented on the map as it is just one unit of the Cuyahoga Group or Formation and is not mapped separately.

OH Maxville Limestone; Rushville, Logan, and Cuyahoga Formations, undivided [Mlc].

PA Cuyahoga Group [Mc], Shanango Formation through Cuyahoga Group, undivided [Msc], and Burgoon Sandstone through Cuyahoga Group, undifferentiated [Mbc]. These units were added in PA to eliminate a very strongly apparent State-line boundary problem, even though there is no mention of Buena Vista Sandstone Member in PA.

THE SAME UNITS APPLY TO BLACK HAND SANDSTONE MEMBER (BELOW):

BLACK HAND SANDSTONE MEMBER OF THE CUYAHOGA FORMATION (AND ASSOCIATES). LOWER MISSISSIPPIAN. (BERYL GREEN)

Black Hand is uppermost member of the Cuyahoga Formation. It is vastly overrepresented on the map as it is just one unit of the Cuyahoga Group or Formation and is not mapped separately, except for a small area in OH.

On the map, this unit covers the same area as Buena Vista in addition to the Black Hand Sandstone Member of Cuyahoga Formation [Mcb], mapped only in OH.

OH Black Hand Sandstone Member of Cuyahoga Formation [Mcb] and Maxville Limestone; Rushville, Logan, and Cuyahoga Formations, undivided [Mlc].

PA Cuyahoga Group [Mc], Shanango Formation through Cuyahoga Group, undivided [Msc], and Burgoon Sandstone through Cuyahoga Group, undifferentiated [Mbc]. These units were added in PA to eliminate a very strongly apparent State-line boundary problem, even though there is no mention of Buena Vista Sandstone Member in PA.

THE SAME UNITS APPLY TO BUENA VISTA SANDSTONE MEMBER (ABOVE).

POTTSVILLE GROUP, CONTAINING SHARON AND MASSILLON SANDSTONES (AND ASSOCIATES). PENNSYLVANIAN. (LEPIDOLITE LILAC)

SHARON AND MASSILLON SANDSTONES

The Sharon sandstone and the Massillon sandstone are informal units within the Pottsville Group in OH (Wolfe, 2013). Sharon sandstone is a bed within the Sharon Conglomerate Member at the base of Pottsville Group, whereas the Massillon sandstone overlies limestone and coal deposits about mid-level the group (Ohio Division of Geological Survey, 1990 [rev. 2000, 2004]). These units cover the same mapped area. Pottsville also occurs in AL and TN and east into PA and WV, but the frac sand description only mentions OH for Sharon.

OH Allegheny and Pottsville Groups, undivided [IPap].

MD Allegheny Formation and Pottsville Formation [Pap].

PA Pottsville Formation [Pp].

WV Pottsville Group [Pnpv].

DEADWOOD FORMATION (AND ASSOCIATES). UPPER CAMBRIAN AND LOWER ORDOVICIAN. (ULTRA BLUE)

A proposed frac sand project is in eastern Pennington County, SD. Deadwood Formation is not shown west of the Black Hills.

WY Bighorn Dolomite, Gallatin Group, Gros Ventre Formation, Snowy Range Formation, Pilgrim Limestone, Park Shale, Meagher Limestone, Wolsey Shale, Flathead Sandstone, Whitewood Dolomite, and Winnipeg and Deadwood Formations, undivided [O_].

SD Whitewood Limestone, Winnipeg Formation, and Deadwood Formation, undivided [OCwd].

WHITE RIM AND CEDAR MESA SANDSTONE MEMBERS OF THE CUTLER FORMATION (AND ASSOCIATES). LOWER PERMIAN. (ANEMONE VIOLET)

White Rim and Cedar Mesa Sandstone Members are subunits of the Cutler Formation. (State maps refer to these units as formations within the Cutler Group.) The entire Cutler Group is shown, as the subunits of interest were not differentiated in the data.

UT Cutler Group [P1]. Only Cutler Group in Emery County is shown. All other Cutler Group in the rest of the State has been removed from this map as it has not been mentioned as having frac sand potential outside Emery County.

WINGATE SANDSTONE (AND ASSOCIATES). UPPER TRIASSIC TO LOWER JURASSIC. (LEPIDOLITE LILAC)

Wingate Sandstone is in the Glen Canyon Group. It is divided into two members: Rock Point (basal), and Lukachukai (upper) Members. There is considerable overlap with mapped units containing the Navajo Sandstone, above.

AZ Glen Canyon Group [Jcg].

CO Morrison, Curtis, Entrada, Glen Canyon, Chinle, and Kayenta Formations; Glen Canyon, Wingate Sandstones.

- Morrison, Curtis, Entrada, and Glen Canyon Formations [J@mg].
- Glen Canyon Sandstone [J@g].
- Glen Canyon Group and Chinle Formation [J@gc].
- Wingate Sandstone and Chinle Formation [@wc].
- Kayenta Formation, Wingate Sandstone, and Chinle Formation [@kc].

NM Rock Point Formation of Chinle Group [@rp], specific terminology in NM.

UT Glen Canyon Group [Jg].

NAVAJO SANDSTONE (AND ASSOCIATES). LOWER JURASSIC. (SOLAR YELLOW)

Navajo Sandstone is the uppermost formation in the Glen Canyon Group. It is correlated with the Nugget Sandstone in Wyoming and with the Aztec Sandstone in NV. There is considerable overlap with units containing the Wingate Sandstone, below.

AZ Glen Canyon Group [Jgc].

CO Mapped units contain Glen Canyon (both as Sandstone and Group), Morrison, Curtis, Entrada, and Chile Formation.

- Morrison, Curtis, Entrada, and Glen Canyon Formations [J@mg].
- Glen Canyon Sandstone [J@g].
- Glen Canyon Group and Chinle Formation [J@gc].

NV Aztec Sandstone [JTRa], an equivalent of the Navajo Sandstone.

UT Glen Canyon Group, Navajo and Nugget Sandstones, Kayenta and Moenave Formations.

- Glen Canyon Group [Jg].
- Navajo Sandstone, Kayenta and Moenave Formations [Jg].
- Nugget Sandstone [Jg].
- Navajo Sandstone (Star Range and Blue Mountain) [Jg].
- Navaho/Nugget Sandstone [Jg].
- Nugget (Navajo) Sandstone [Jg].

WY Gypsum Spring, Sundance, and Chugwater Formations; Nugget Sandstone.

- Gypsum Spring Formation and Nugget Sandstone [J@gn].
- Sundance and Gypsum Spring Formations and Nugget Sandstone [J@].
- Gypsum Spring Formation, Nugget Sandstone, and Chugwater Formation [J@gc].
- Nugget Sandstone, Ankareh Formation, Thaynes Limestone, Woodside Shale, Chugwater, and Dinwoody Formation [J@nd].
- Cloverly, Morrison, Sundance, and Gypsum Spring Formations, and Nugget Sandstone [K@].
- Nugget Sandstone. [J@n].

WHITE THRONE MEMBER OF THE TEMPLE CAP FORMATION. MIDDLE JURASSIC. (WHITE DOTS)

UT Only described in Kane and Washington Counties. (Temple Cap Formation is a basal unit of the San Rafael Group.)

White Throne Member is not shown as a map unit, but indicated in southwest UT with white dots where exposed in walls of deep canyons at:

-112.68685 longitude, 37.20481 latitude

-112.85086 longitude, 37.24193 latitude

(WGS 84 Coordinate System)

PAGE SANDSTONE (AND ASSOCIATES). MIDDLE JURASSIC. (ROSE QUARTZ)

Page Sandstone is a basal unit of the San Rafael Group. It is not mapped individually in any of the State maps. All units that specified upper San Rafael Group have been removed. Map units will overlap with Entrada Sandstone.

AZ San Rafael Group [Js].
NM San Rafael Group [Jsr].
UT San Rafael Group [J1]. Only one polygon in the entire State.

ENTRADA SANDSTONE, PART OF SAN RAFAEL GROUP (AND ASSOCIATES). MIDDLE JURASSIC. (TZAVORITE GREEN)

AZ San Rafael Group [Js].

CO Entrada is not mapped separately. Mapped units containing Entrada include: Exeter Formation, Morrison Formation, Summerville Formation, Curtis Formation, Ralston Creek Formation, Wanakah Formation, Chinle Formation, Glen Canyon Formation, Dakota Formation, Purgatoire Formation, Burro Canyon Formation. [Entrada Sandstone in Colorado includes (alphabetical): Dewey Bridge Member, Moab Member or Moab Tongue, Rehoboth Member, and Slick Rock Member. San Rafael Group in Colorado includes (alphabetical): Carmel Formation, Curtis Formation, Entrada Sandstone, Summerville Formation, Temple Cap Formation or Temple Cap Sandstone, Todilto Formation or Todilto Limestone, and Wanakah Formation.]

- Morrison Formation, Summerville Formation, and Entrada Sandstone [Jmse].
- Morrison, Curtis, and Entrada Formations [Jmce].
- Morrison Formation and Entrada Sandstone [Jme].
- Morrison, Ralston Creek, and Entrada (or Exeter) Formations [Jmre].
- Morrison, Wanakah, and Entrada Formations [Jmwe].
- Morrison, Entrada, and Chinle Formations [J@mc].
- Morrison, Curtis, Entrada, and Glen Canyon Formations [J@mg].
- Dakota, Purgatoire, Morrison, Ralston Creek, and Entrada Formations in southeast [KJde].
    - Dakota, Morrison, and Entrada Formations in central mountains.
    - Dakota, Burro Canyon, Morrison, Wanakah, and Entrada Formations in Gunnison River area.
    - Dakota, Morrison, Curtis, and Entrada Formations in northwest.

NM Mapped as Entrada Sandstone, San Rafael Group, Morrison Formation and upper San Rafael Group, and Zuni and Entrada Sandstones, undivided. In NM the San Rafael Group includes (alphabetical): Bell Ranch Formation, Bluff Sandstone, Carmel Formation, Curtis Formation, Entrada Sandstone, Summerville Formation, Thoreau Formation, Todilto Formation, and Wanakah Formation.

- San Rafael Group [Jsr].
- Entrada Sandstone [Je].
- Morrison Formation and upper San Rafael Group [Jmsu].
- Zuni and Entrada Sandstones, undivided [Jze].

OK Exeter is used as an equivalent name to the Exeter Member of Entrada Sandstone of San Rafael Group in NM. Exeter (Entrada) Sandstone [Je].

UT Subunits of the San Rafael Group in UT include (alphabetical): Carmel Formation, Curtis Formation, Entrada Sandstone, Henrieville Sandstone, Page Sandstone, Romana Sandstone, Summerville Formation, Temple Cap Formation or Temple Cap Sandstone, Todilto Formation or Todilto Limestone, and Wanakah Formation. Curtis Formation, Entrada Sandstone, and Carmel Formation [J1].

QUATERNARY AEOLIAN DUNE SANDS. QUATERNARY. (CHERRY COLA)

UT There is Quaternary aeolian dune sands (Qe) in most of the State, but only the bodies in Washington and Kane Counties (southwest corner of State) have been described as potential frac sand sources. All of the Qe polygons outside those two counties have been removed (per Rupke, 2014); polygons overlapping those counties are retained.

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