Unconventional Fossil Fuels Nomenclature: *Inside on Page 20*

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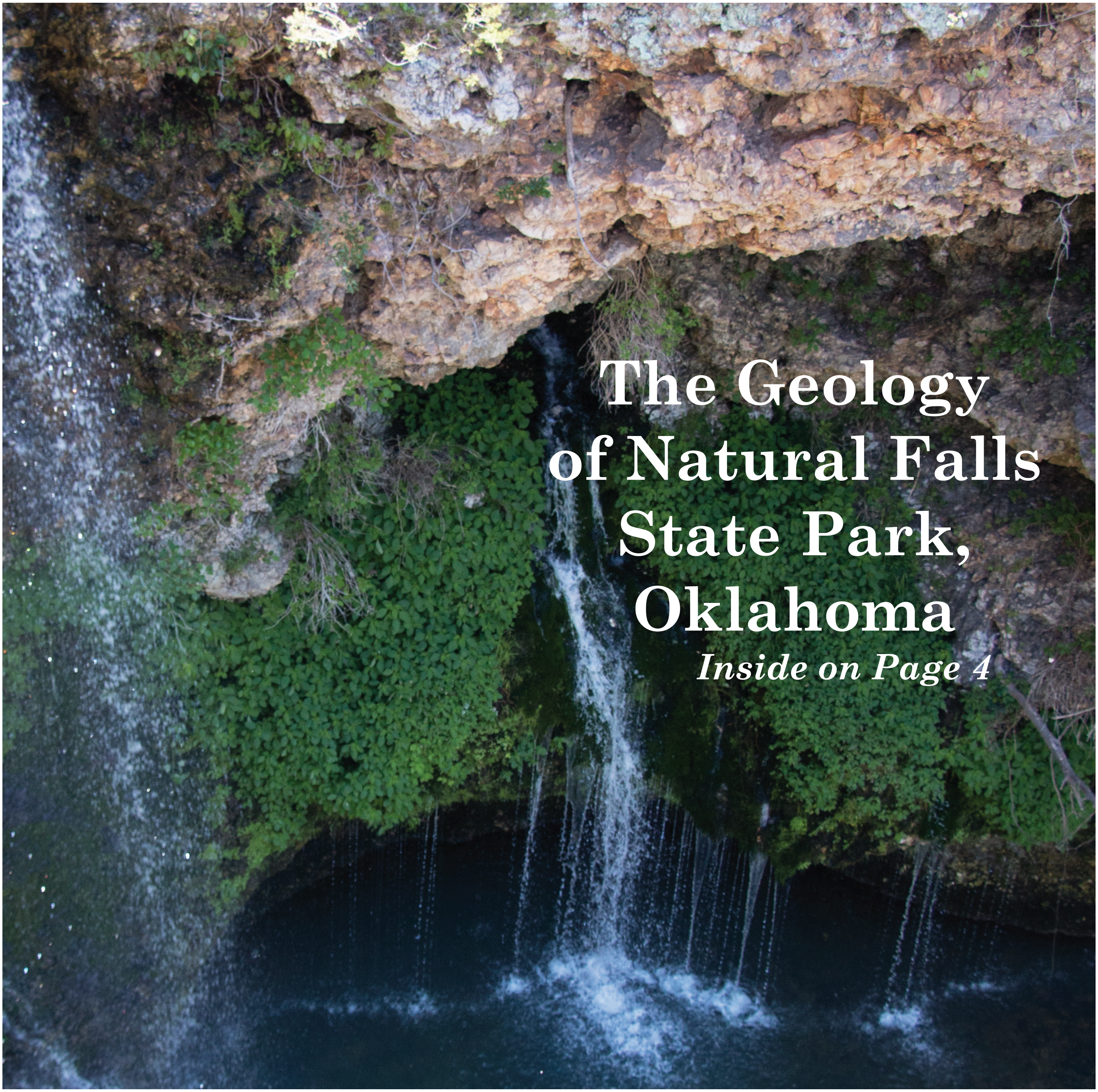

The Geology of Natural Falls State Park, Oklahoma

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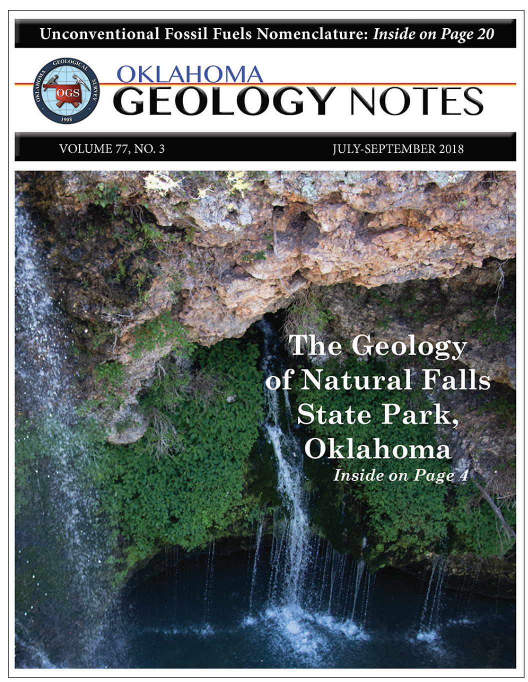
The Oklahoma Geological Survey is a state agency for research and public service, mandated in the State Constitution to study Oklahoma's land, water, mineral and energy resources and to promote wise use and sound environmental practices.

IN THIS ISSUE

OGS researchers explore the geology of Natural Falls State Park located in northeast Oklahoma. — ***Inside on Page 4***

Also, unconventional fossil fuels nomenclature. — ***Inside on Page 20***



Cover photo is from Natural Falls State Park
Photo and Cover Design by Ted Satterfield

From The Director

Natural Falls State Park and Unconventional Fossil Fuels Nomenclature

This edition of the Oklahoma Geology Notes includes two articles that address different aspects of the Oklahoma Geological Survey's mission to disseminate the results of its investigations to promote the wise use of the state's resources. The first, by Julie Chang, Stacey Evans, and Russell Standridge, describes the geological features that make one of our state parks significant and discusses how they formed. It is directed at a wide audience of students, educators, and the general public. The second is more focused on technical details of the terminology of unconventional oil and gas resources, and is directed at the industry, as well as at state agencies and other government officials, and at the financial and media communities that also play an important role in how these resources are developed.

Natural Falls, the centerpiece of Natural Falls State Park in Delaware County, near the Arkansas border, is tied with Turner Falls as the highest waterfall in the state. The cover article for this issue describes the geologic setting of the park, including the history of the marine sediments that form the bedrock in the park, and the erosional activity that is responsible for the formation of the falls. It also points out the difference in mode of formation of Natural Falls and Turner Falls. The first is formed by dissolution of the calcium carbonate that makes up the limestone beneath the cap rock of the falls, whereas the latter is formed by continuing precipitation of the same mineral along the bed of the stream, which has built Turner Falls. These geologic details illustrate the diversity of landforms in Oklahoma, and how they were built, with the purpose of helping many Oklahomans understand the history and current state of the land they share.

The second article, by Robert Kleinberg and myself, is a note on the names we apply to unconventional oil and gas reservoir rocks and the resources produced from them. These unconventional resources constitute a major energy source for Oklahoma and the nation. Their development has come to dominate the oil and gas industry here, and to influence energy markets and geopolitical interactions around the world. The development of these resources has come to be called the "Shale Revolution."

Jeremy Boak
OGS Director

Ironically, many of the rock formations that have enabled the United States to set new records for production are not actually shale, by any of the numerous defining criteria for shale. Mudstone is a major very low permeability reservoir type for what is called "gas shale." However, the best reservoirs contain low abundances of clay minerals (a defining feature of shale), which makes them brittle enough to be fractured hydraulically, and to produce gas. The formations now producing oil and called by analogy "oil shale" are even less like shale: while they also require hydraulic fracturing to be economically productive, they are more like tight gas sandstones in their rock properties.

Although the distinctions made in this note may seem purely academic, multi-million dollar projects have moved forward despite trade restrictions because a company was able to show that restrictions on "shale technology" did not apply given that the tight rock formation targeted was not a shale.

These articles display the wide range of investigations that fall under our constitutional mission, and the diversity of work carried out by OGS staff in pursuit of that mission. They also give some hint why we are rarely bored with our work!

The Geology of Natural Falls State Park, Oklahoma

By
JULIE M. CHANG, STACEY C. EVANS, and G. RUSSELL STANDRIDGE
OKLAHOMA GEOLOGICAL SURVEY

INTRODUCTION

Natural Falls State Park (hereafter abbreviated either "Natural Falls" or the "park") is located in the Ozark Uplift area of northeastern Oklahoma. Natural Falls became an Oklahoma State Park in 1990 and features a 77-foot tall waterfall that ties Turner Falls for the tallest waterfall in Oklahoma. The rock that forms the falls lies within the Mississippian Boone Formation, which is composed primarily of chert and limestone. Natural Falls is located in Delaware County in northeastern Oklahoma, near the Oklahoma-Arkansas Border (Fig. 1). West Siloam Springs, approximately six miles to the east, is the closest town. The park occupies 120 acres (Oklahoma State Parks, 2018a; Wikipedia, 2018). The park's waterfall (Fig. 2a) can be observed from a platform near the top of the falls (Fig. 2b), as well as from an observation deck with benches at the bottom of the falls (Fig. 2c).

Prior to establishment as a state park, the Natural Falls area was called "Dripping Springs," and the falls were called "Dripping Springs Falls." As there was a "Dripping Springs State Park" already in existence near Okmulgee, this area had to take on a different name when it became a state park; however, many locals still use the older names.

The waterfall at the park is 77 feet high, which ties Turner Falls as the highest waterfall in Oklahoma (Oklahoma's Waterscapes, Falls & Cascades, 2018). These two waterfalls, though, are geologically quite different. At Natural Falls, the waterfall occurs where Dripping Springs Branch falls over a cliff into a deep v-shaped ravine (Fig. 2a). Here, more resistant rocks cap weaker rocks, and the weaker underlying rocks were more easily eroded by the flowing stream. As the weak strata were eroded and that portion of the stream became topographically lower and lower, the overlying more resistant rocks remained nearly unchanged, resulting in the sharp drop in elevation that is characteristic of waterfalls. This type of waterfall tends to retreat upstream as erosion of the weak strata leads to undercutting of the more resistant strata. Eventually the resistant cap rock will lose support, break off, and the crest of the waterfall will move further upstream.

In contrast, Turner Falls is formed by an additive process rather than a reductive, erosive process. The waters that flow over Turner Falls contain dissolved calcium carbonate. The deposition of this calcium carbonate in the form of travertine built up the falls (Ham et al., 1973).

HISTORY OF THE NATURAL FALLS STATE PARK AREA

The following presents a timeline of recent

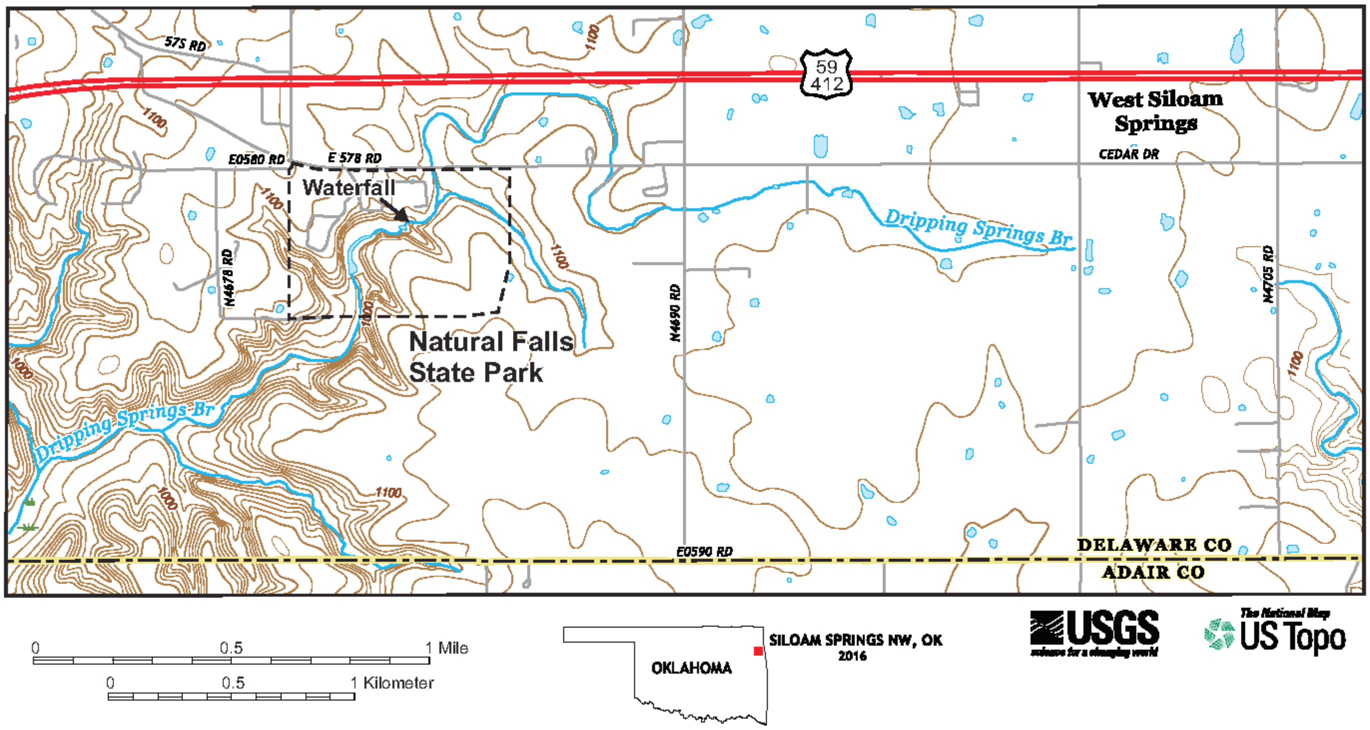


Figure 1. Part of the USGS Siloam Springs NW, OK, 7.5' quadrangle showing the location of Natural Falls State Park.

Figure 2: (a, left) Picture of the waterfall at Natural Falls State Park. (b, top right) Picture of the observation platform near the top of the falls. (c, bottom right) Picture of the observation deck with benches near the bottom of the falls.

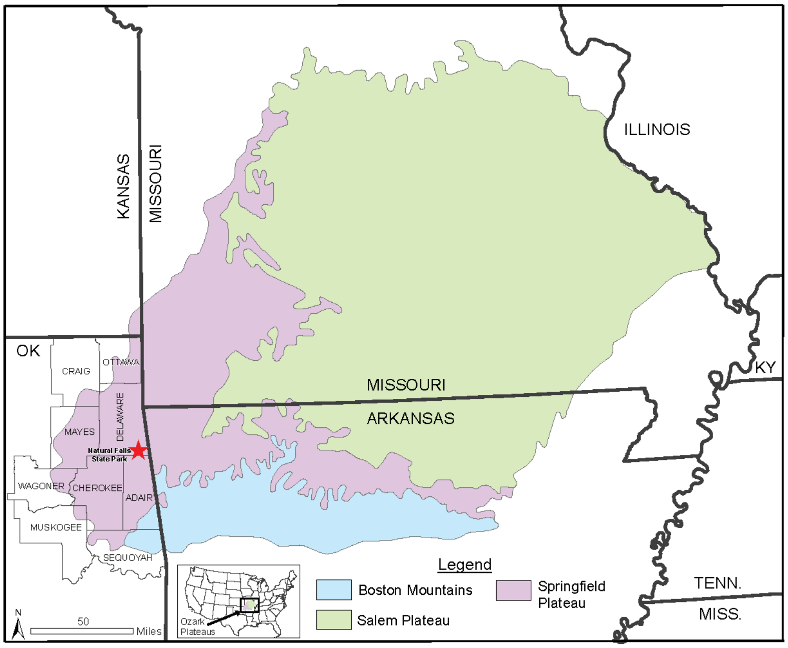


Figure 3. Map of the physiographic provinces of the Ozark Uplift. Modified from Knierim et al., 2017.

events in the area, leading up to the designation of the state park at Natural Falls:

- "The lands of northeastern Oklahoma were given originally to the Cherokee Nation through the Removal Treaty of 1838" (Huffman et al., 1963, p. 20). Chert in the area had been used to make arrowheads and other implements by native people (Gould, 1921).

- During the Civil War (1861-1865) and following years, the area was a hideout for outlaws. There have been stories of people finding Civil War-Era bombs in the park (Tracey Robertson, Park Manager, personal communication, 2017).

- In 1907, Oklahoma became a state.

- In 1908, the Ozark National Forest was established by President Theodore Roosevelt.

- In 1974, the movie "Where the Red Fern Grows" was filmed in the area that is now Natural Falls (Oklahoma State Parks, 2018a).

- In 1986, the Ozark Plateau National Wildlife Refuge was established by Congress.

- Before becoming a state park, the area was privately owned and operated as a tourist attraction (Tracey Robertson, Park Manager, personal communication, 2017)

- In 1990, Natural Falls became a state park (Wikipedia, 2018).

GEOLOGY AND GEOGRAPHY

The park is located in the Ozark Uplift of Oklahoma (Fig. 3). The Ozark Uplift is a regional asymmetrical uplift encompassing ~40,000 square miles in four states (NW Arkansas, SE Kansas, NE Oklahoma, and S Missouri) (Huffman, 1958). The apex of the uplift is located in the St. Francois Mountains of southeastern Missouri, where ~1.48 billion years old Precambrian rocks (Rohs and Van Schmus, 2007) are exposed at the surface. Rocks dip away from this apex in all directions. Rising of the Ozark Uplift is thought to have occurred during the Ordovician (~485-445 Ma) and Devonian (~420 Ma-355 Ma), as well as during the Late Pennsylvanian (~300 Ma) Ouachita Orogeny (Cox, 2009). Additionally, four deformational events in the Ozark Uplift are thought to have occurred during the Pennsylvanian (~325-300 Ma).

The Ozark Uplift is divided into three main physiographic regions: the Salem Plateau, the Springfield Plateau, and the Boston Mountains (Fig. 3). A plateau is a flat-topped area of uplifted land; streams have dissected the plateaus of the Ozark Uplift, providing good outcrop exposures and numerous recreational opportunities that attract visitors to the area.

In general, the Ozark Uplift increases in elevation and exposes younger rocks to the south. The Salem Plateau is capped by Ordovician (~485-445 Ma) and older rocks, primarily dolostone; the Springfield Plateau is capped primarily by Mississippian (~365-330 Ma) limestone and chert; and the Boston Mountains are capped by Early and Middle Pennsylvanian (~325-310 Ma) rocks, mostly sandstone (Huffman, 1953; Simms et al., 1995). In the Springfield and Salem Plateaus, deep, v-shaped stream valleys have been cut 200-300 feet below the surrounding surface and exhibit a characteristic dendritic drainage pattern (Huffman et al., 1963). In the Boston Mountains, valleys have been cut even deeper, 300-500 feet below the

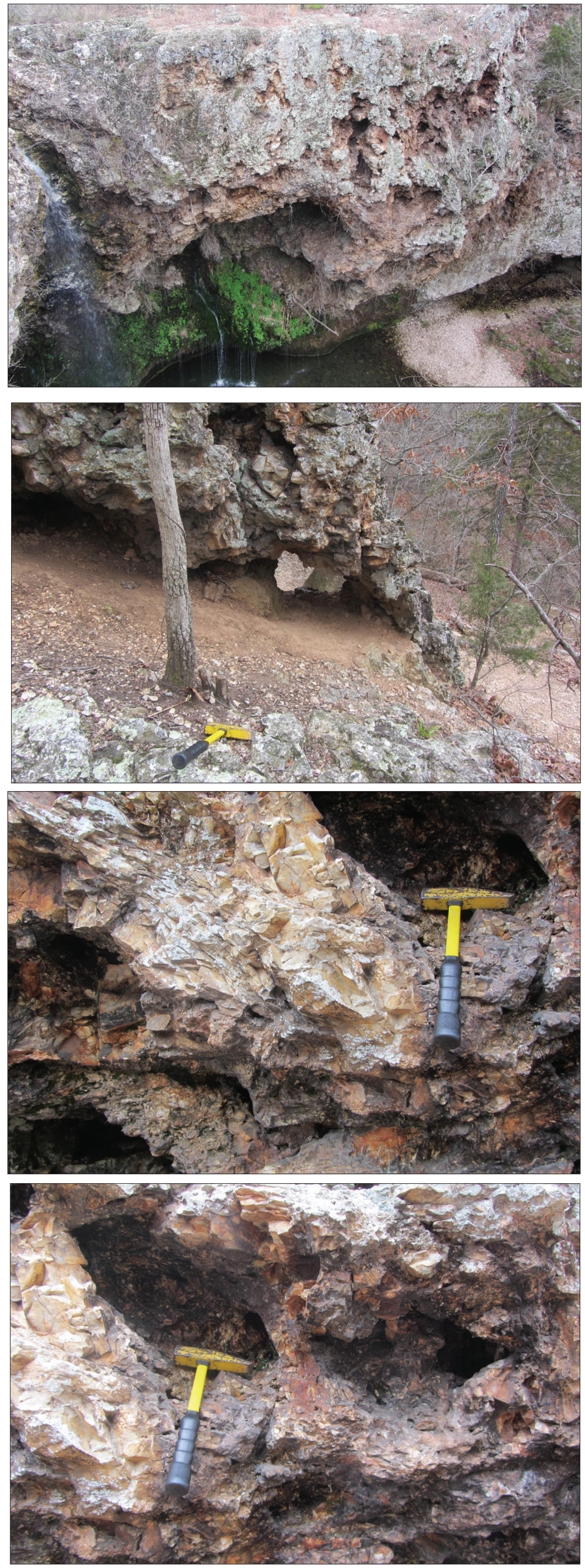


Figure 4. (a, above; b-c, top right) Pictures showing ragged and holey nature of the rocks at Natural Falls State Park. (d-e, bottom right) Pictures showing light-colored rocks with iron staining and fractures.

surrounding surface.

In Oklahoma, the Ozark Uplift is bounded by the Arkansas River Valley on the south and the Grand and Spring Rivers on the west (Huffman, 1958). Only the Springfield Plateau and the Boston Mountains regions occur in Oklahoma. The park is located in the Springfield Plateau region of the Ozark Uplift, at an elevation of ~1000-1100 feet (Fig. 1).

Based on a brief examination, the outcrops observed at the park are ragged and contain many holes and indentations (Fig. 4a-c). The rocks themselves are composed of chert that is non-porous, fractured, and light-colored with iron-staining (Fig. 4d, e). Holes and indentations may be a result of limestone erosion.

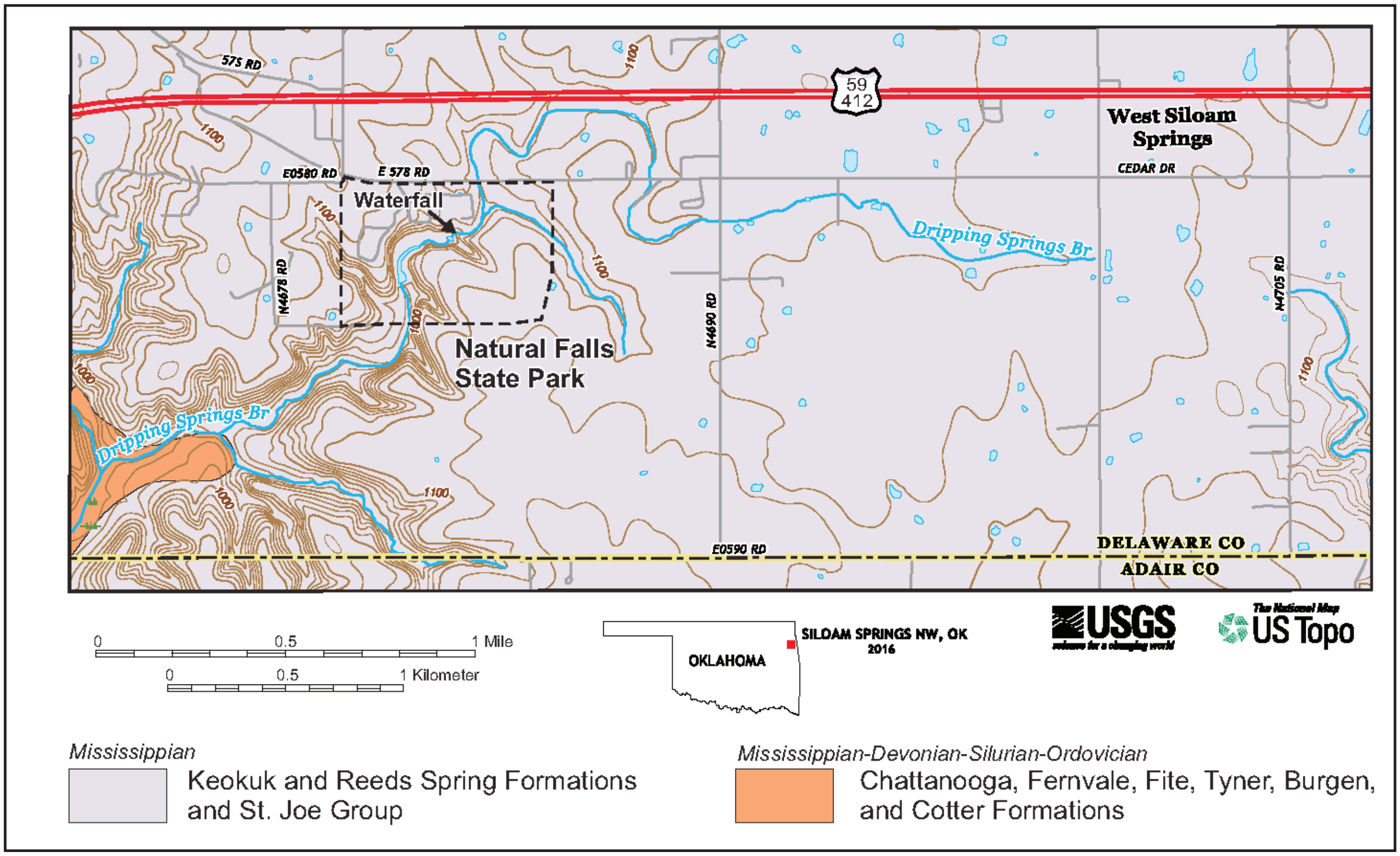


Figure 5. Part of the USGS Siloam Springs NW, OK, 7.5' quadrangle showing the location of Natural Falls State Park. Overlying geology is from Cederstrand, 1997.

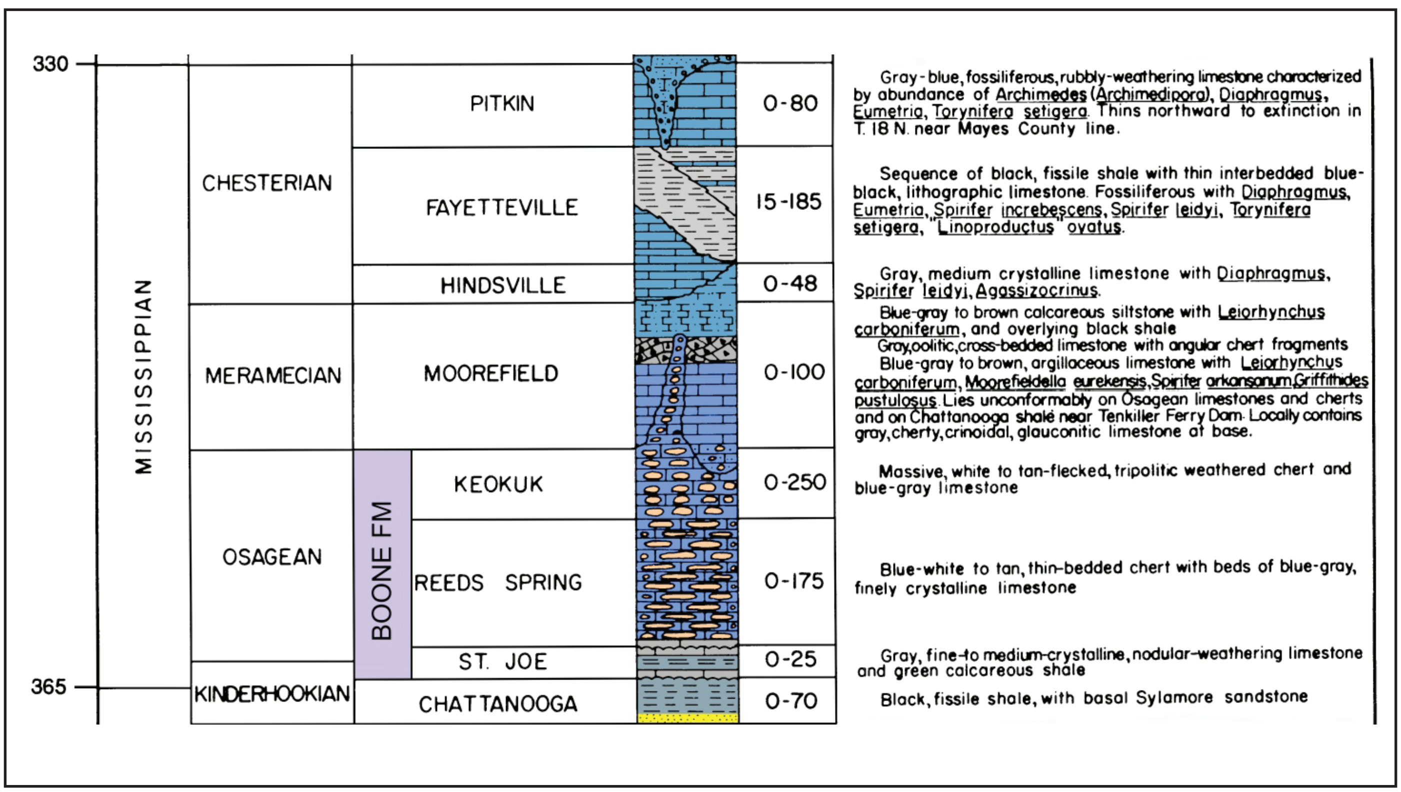


Figure 6. Stratigraphic column for northeastern Oklahoma. Modified from Huffman (1958).

Figure 7. Picture of springs near the base of the waterfall at Natural Falls State Park.

GENERAL STRATIGRAPHY

The rocks exposed at Natural Falls are primarily Mississippian chert-bearing limestones of the Boone Formation (Fig. 5, Fig. 6; Miser et al., 1954; Marcher and Bingham, 1971; Cederstrand, 1997). According to Bingham (1969), springs below the waterfall (e.g., Fig.7) flow from openings in the Reeds Spring Member of the Boone Formation.

Historically, most studies of Mississippian stratigraphy in northeastern Oklahoma were focused on the Tri-State Zinc-Lead Mining District because of its economic importance (e.g., Fowler and Lyden, 1932; Fowler, 1933; Fowler, 1935; McKnight and Fischer, 1970). Over time, changes to the stratigraphic interpretation have been made as more geologic data are acquired in an area. Even today, revisions to Mississippian stratigraphy in northeastern Oklahoma continues (e.g., Mazzullo et al., 2011; Mazzullo et al., 2013; Boardman II et al., 2013; Mazzullo et al., 2016; Miller, 2016; Godwin, 2017; Godwin, 2018). Much of the most recent stratigraphic work has been based on studies of conodont fossils.

Early workers classified the Boone Formation as of late Kinderhookian and Osagean age, including, from oldest to youngest, the St. Joe, Reeds Spring, and Keokuk Members (Fig. 6; Huffman, 1958). Later workers divided the Boone Formation into seven members, including, from oldest to youngest, the St. Joe, Reeds Spring, Grand Falls Chert, Joplin, Short Creek Oolite, Baxter Springs, and Moccasin Bend Members

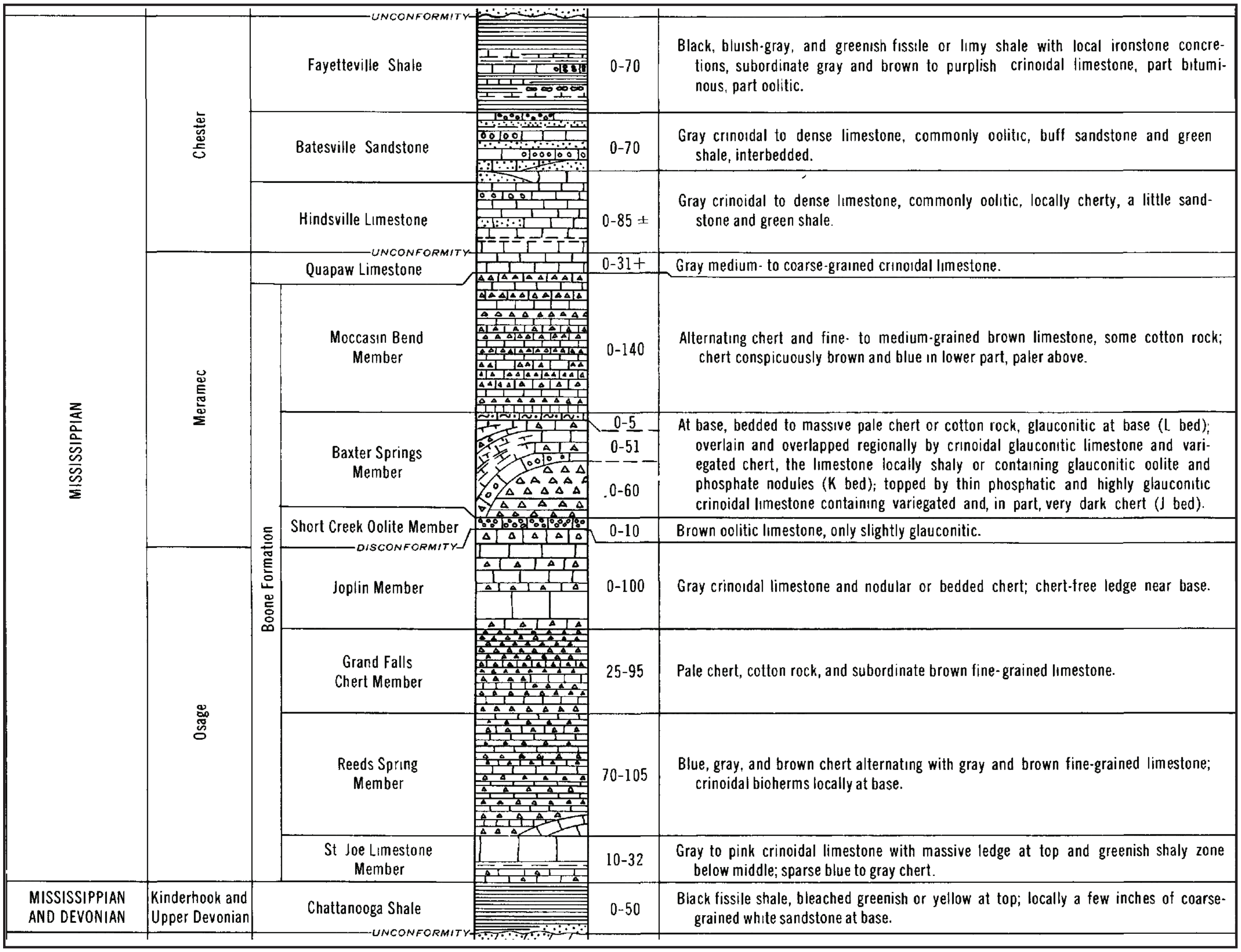


Figure 8. Stratigraphic column for northeastern Oklahoma (McKnight and Fischer, 1970).

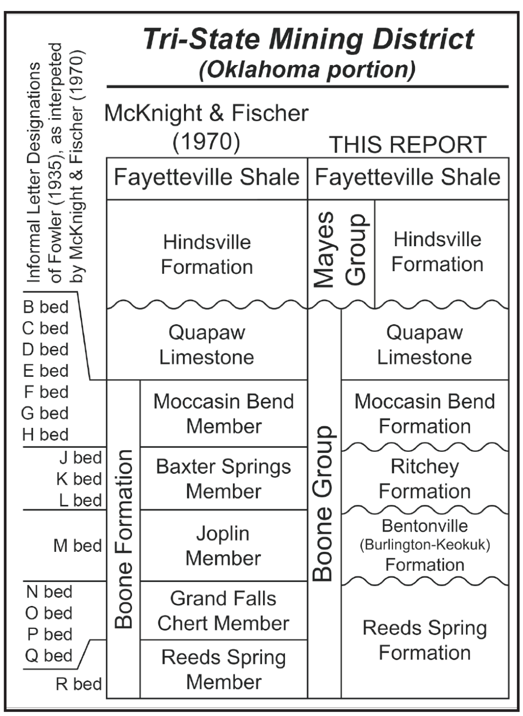


Figure 9. Stratigraphic column for northeastern Oklahoma (Godwin, 2018).

(Fig. 8; McKnight and Fischer, 1970). Most recently, workers have proposed elevating the Boone Formation to Boone Group and including five different formations; from oldest to youngest, these are the Reeds Spring, Bentonville (Burlington-Keokuk), Ritchey, Moccasin Bend, and Quapaw Limestone Formations (Fig. 9; Godwin, 2017; Godwin, 2018).

Workers also suggest that formations within the Boone Group may not be distinguishable lithologically and that faunal data (for example, conodonts) are needed for accurate stratigraphic placement (Godwin, 2018). Thus, a paleontological study would be important to understand the placement of the rocks at Natural Falls within the Boone Group.

DESCRIPTION AND FORMATION OF BOONE FORMATION

The Mississippian Boone Formation consists of limestone and chert with lesser siltstone and shale that are thought to have been deposited in a warm, shallow- to moderate-depth marine ramp environment (Fig. 10) (Blakey, 2011; Mazzullo et al., 2011; Minor, 2013).

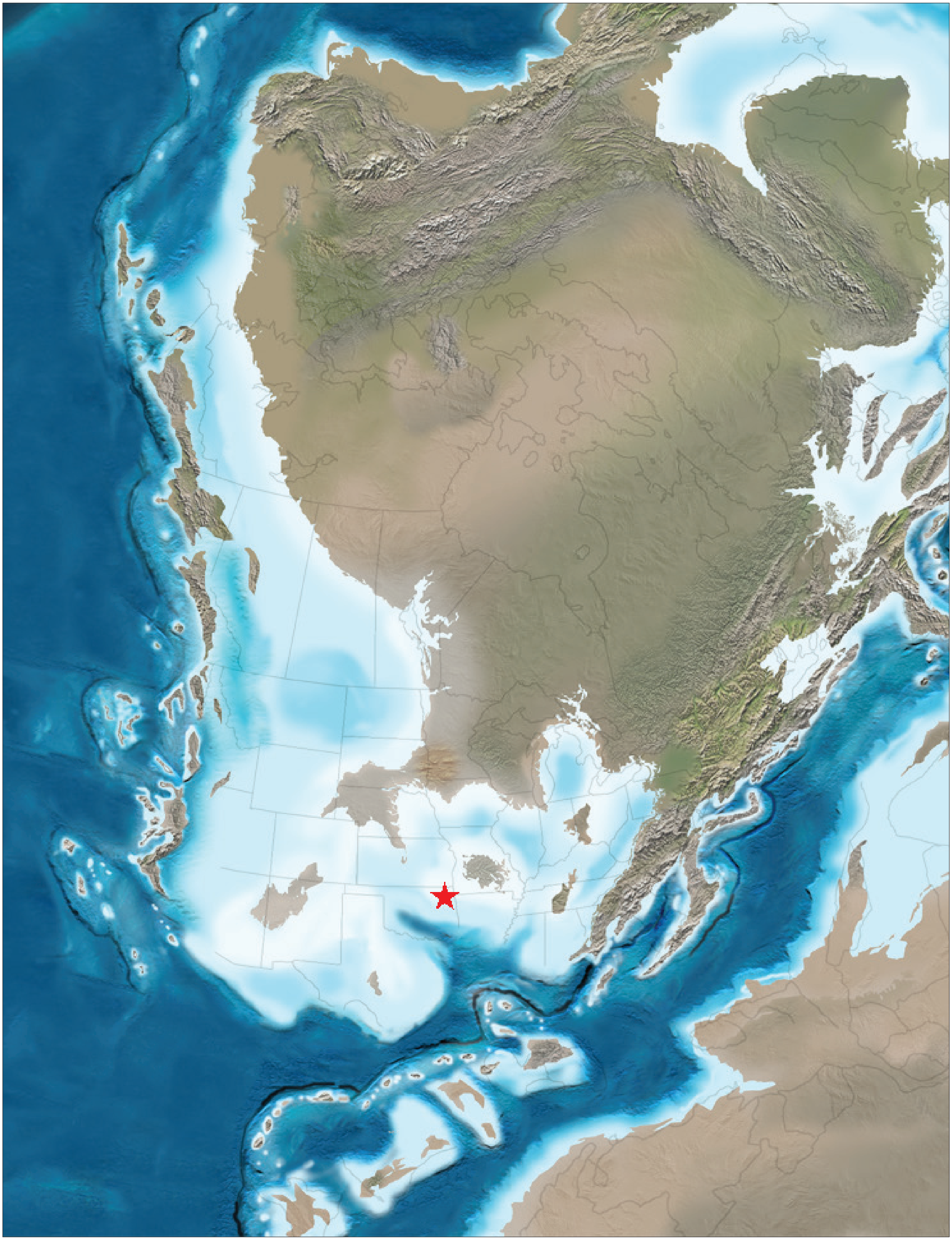


Figure 10. Paleogeographic map of North America for the Early Mississippian (345 Ma) time period (Blakey, 2011). Tan/green = land; pale blue/white = shore; blue = shallow marine; dark blue = deep marine. Red star shows the location of the park.

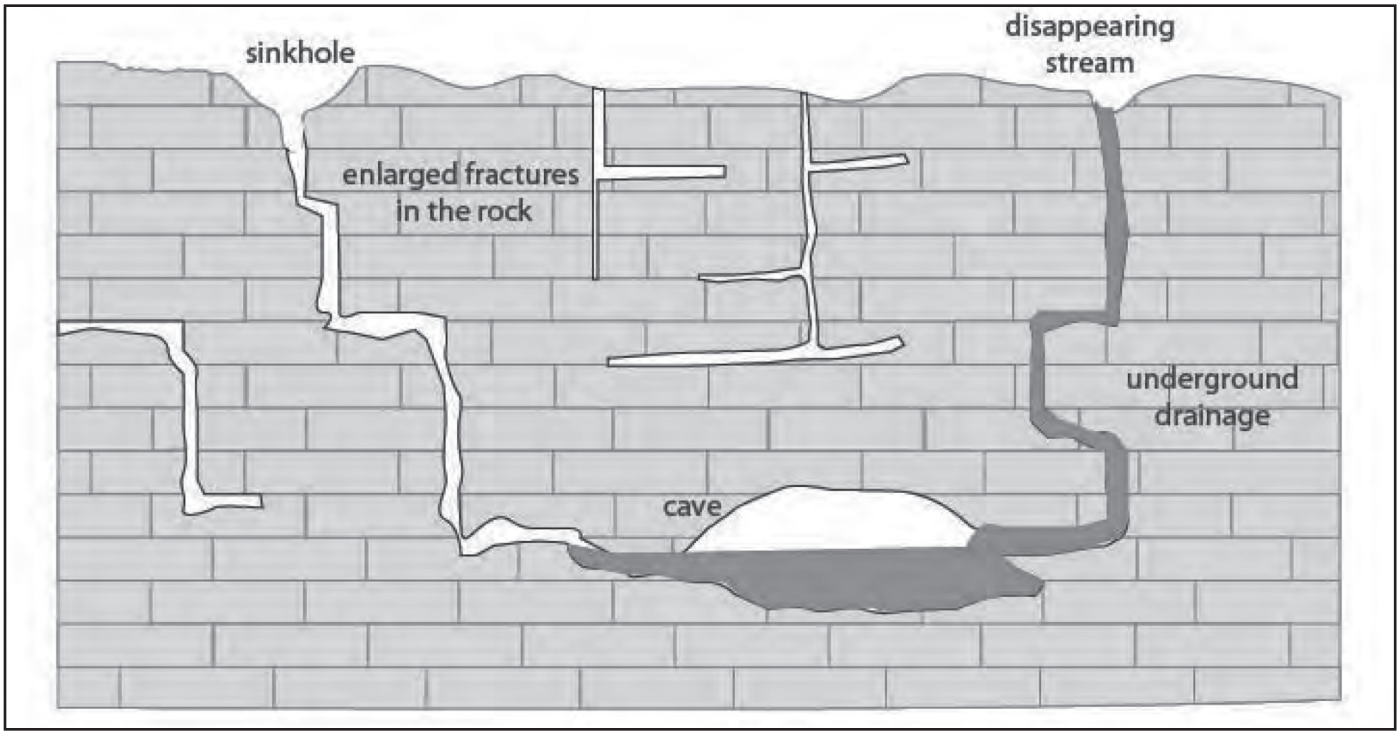


Figure 11. Diagram of karst features (Chandler, 2014).

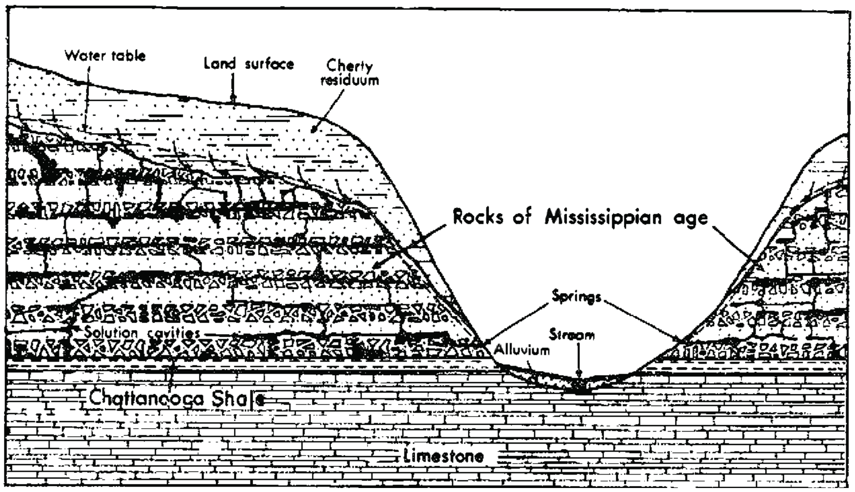


Figure 12. Schematic diagram showing the formation of springs in the Ozark Plateau region (Bingham, 1969).

Most of the fossils found in the rocks are marine invertebrates such as crinoids, brachiopods, and bryozoans (Mazzullo et al., 2011). Chert is thought to have formed both penecontemporaneously with carbonate deposition and as a diagenetic replacement of carbonate (Minor, 2013).

KARST TOPOGRAPHY

Due to the abundance of carbonate rocks (limestone, dolostone) in the Ozark Uplift, karst features are common. Karst forms when acidic groundwater dissolves carbonate rocks, creating features such as caves, sinkholes, disappearing streams, and springs (Fig. 11). Caves and caverns are natural openings in the ground that lack light and are large enough for humans to enter. Sinkholes are depressions or holes in the ground that form from dissolution of rock or by cave collapse. Disappearing streams occur where streams disappear underground due to the flowing or seeping of water into the ground, commonly at sinkholes. Springs form where groundwater emerges at the Earth's surface (Fig. 12).

In the Ozark Uplift region of Oklahoma, springs are common (Fig. 13).

"The springs are more numerous where deep valleys and steep hillsides have been formed by erosion [Fig. 12]. *The Chattanooga Shale* [equivalent to the Woodford Shale in Oklahoma] *crops out in some of the deep valleys and is widely distributed in the subsurface throughout the area. The shale is insoluble and generally impermeable and serves as a barrier to the downward percolation of groundwater. The St. Joe consists of limestone and limy shale. Few springs flow from this formation because the limy shale is a deterrent to the movement of water. The Reeds Spring Formation consists of about equal amounts of thin, alternating layers of dense, fine-grained limestone and dark-gray to blue-gray*

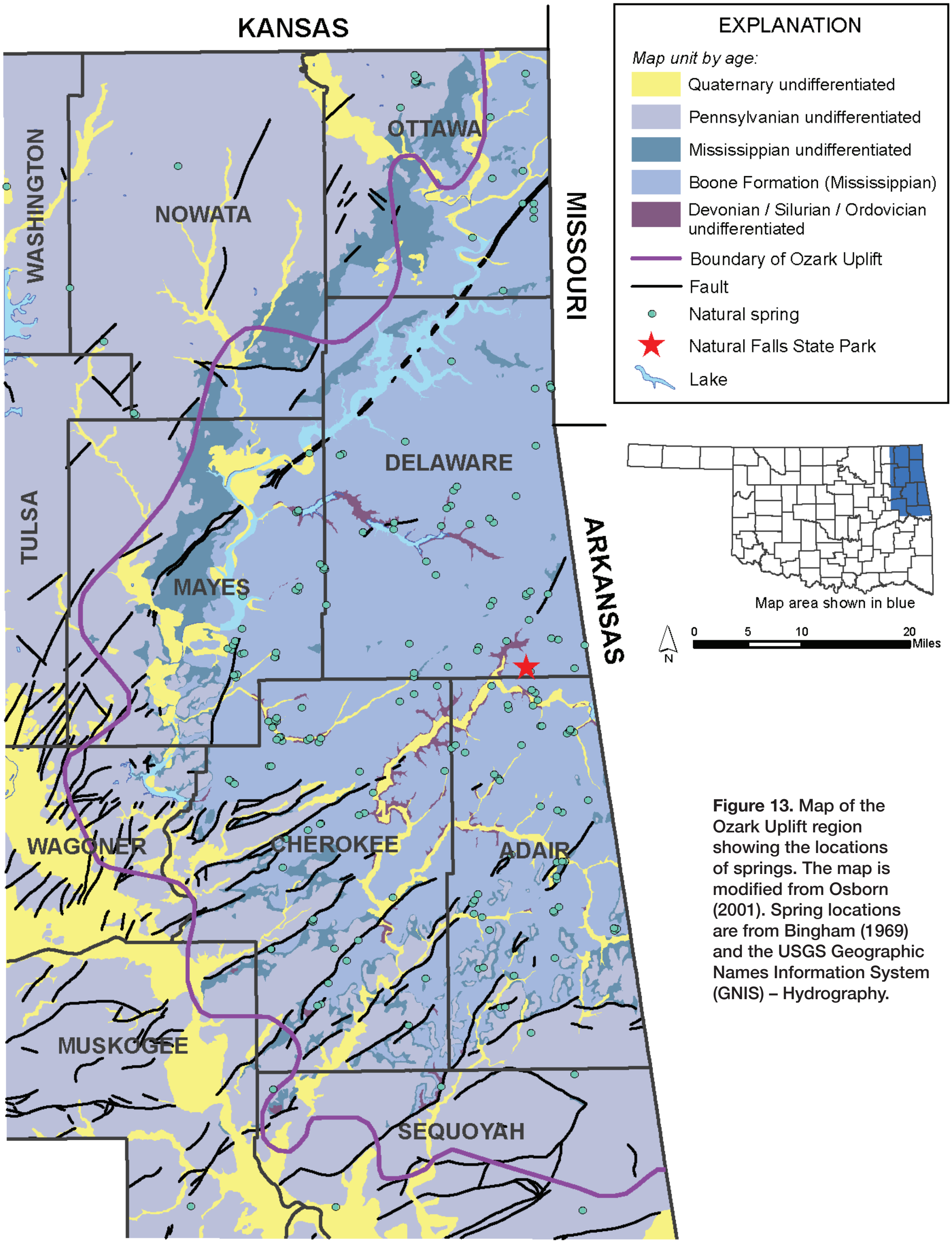
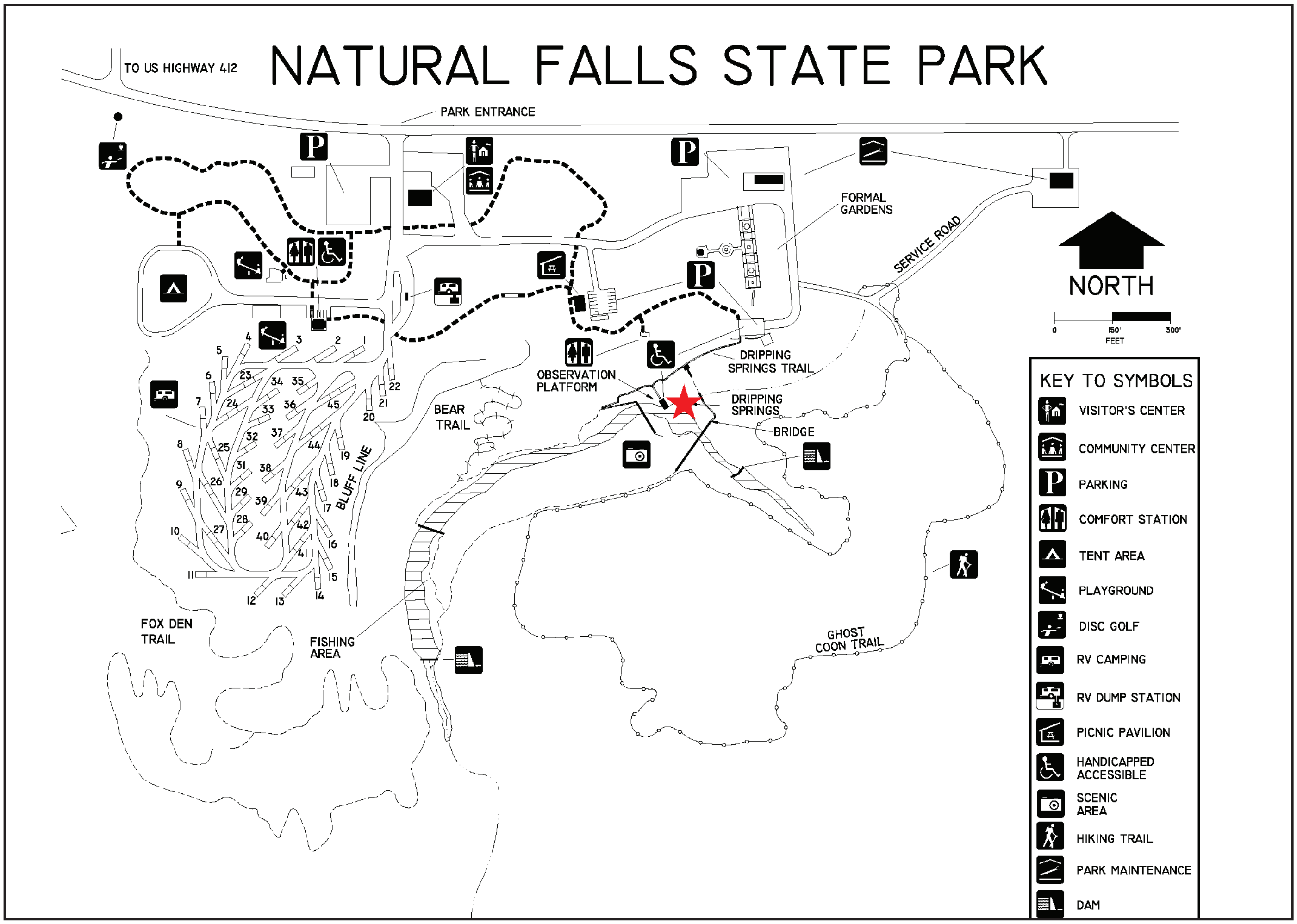


Figure 13. Map of the Ozark Uplift region showing the locations of springs. The map is modified from Osborn (2001). Spring locations are from Bingham (1969) and the USGS Geographic Names Information System (GNIS) – Hydrography.



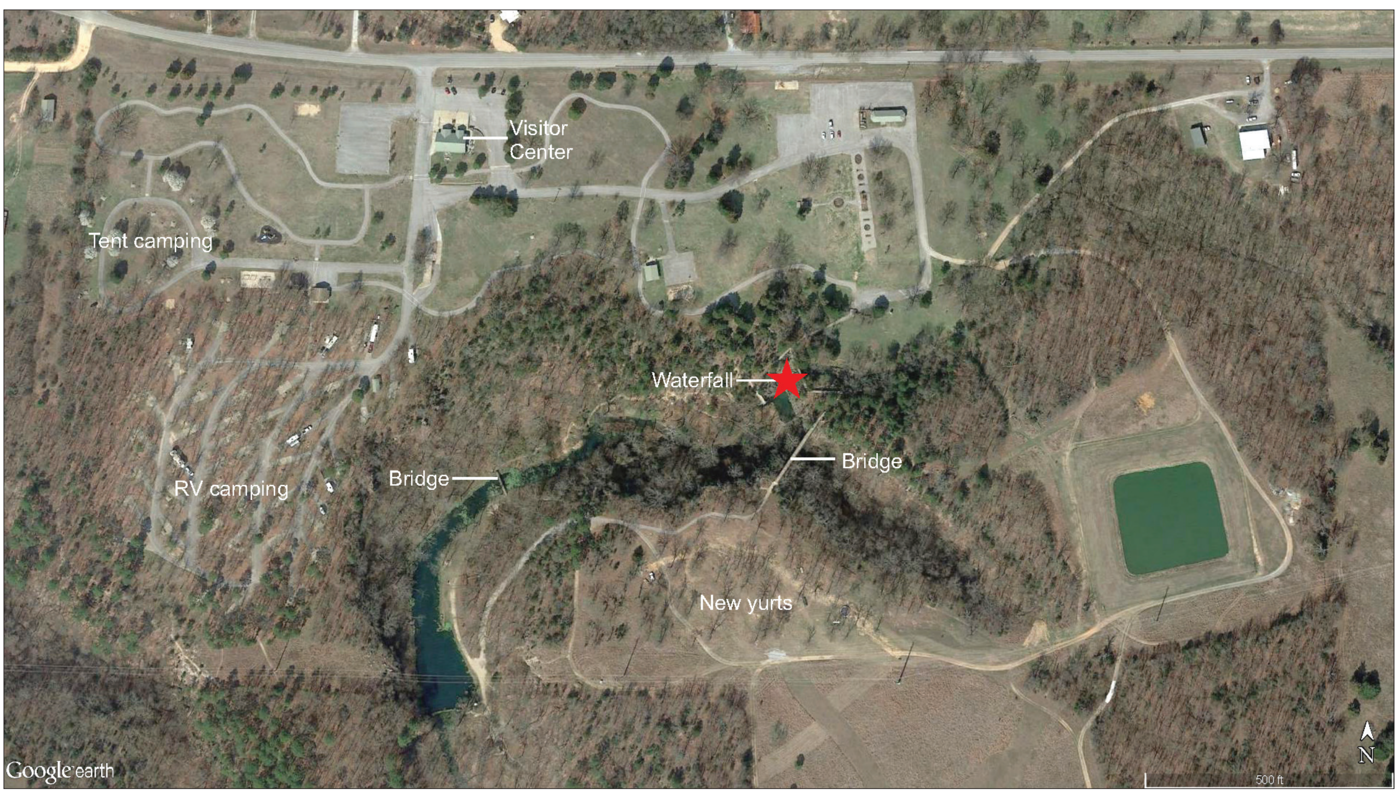


Figure 14a (top). Map of Natural Falls State Park (Oklahoma State Parks, 2018a). Red star shows the location of the waterfall. b (bottom). Google Earth image of Natural Falls State Park (accessed June 2, 2017).

Figure 15. (a, above). Picture of one of the recently constructed yurts at Natural Falls State Park. (b-c, right) Pictures of the interior of a recently constructed yurt at Natural Falls State Park.

chert. The chert layers are resistant to weathering, but, because of brittleness, the chert is subject to fracturing during structural movements. These fractures are the main passageways through which water from precipitation moves downward to the ground water reservoir. The flushing and surging action of the moving water dissolves and abrades some of the limestone between the layers of chert, forming a network of water-filled cavities along bedding planes of the bedrock. Most of the springs in northeastern Oklahoma flow directly from bedding-plane cavities in the Reeds Spring Formation" (Bingham, 1969, pp. 135, 137, 138).

LOCATION AND FACILITIES AT NATURAL FALLS STATE PARK

Over four miles of trails (Fig. 14a, b) allow visitors to explore the falls and creek (Dripping Springs Branch), as well as provide ample hiking opportunities to see the chert-rich formations that are exposed throughout the park. Activities at the park include hiking (4.5 miles of trails); basketball; volleyball; disc golf; horseshoes; and catch and release fishing (Oklahoma State Parks, 2018b). The park also contains picnic tables, grills, playgrounds, and a garden. The Red Fern Reunion Center is available for group activities. The park contains RV and tent sites for camping, as well as a comfort station with showers.

The park has recently completed building five new yurts for overnight camping (Fig. 15a-c). Yurts are circular tents that have been used by nomads on the steppes of Central Asia for at least three thousand years. Yurts are covered with skins or felt, and a layer of thick waterproof fabric. The walls are assembled from latticed sections of light-weight wood (Fig. 15b, c). The roof consists of straight or bent poles attached to a central ring, the crown, which is open to the outside (domed plexiglass can be seen covering the round crown windows in Fig. 15a). These structures are ideal for life on the steppe, where high wind speeds and freezing winters are common. The round shape is resistant to winds from any direction, while the crown window allows for air circulation and a chimney opening for a central heat-providing stove (National Geographic, 2018).

SUMMARY

Natural Falls State Park is located in the Ozark Uplift area of northeastern Oklahoma. It became an Oklahoma State Park in 1990 and features a 77-foot tall waterfall that ties Turner Falls for the tallest waterfall in Oklahoma. The area lies within the Mississippian Boone Formation, which is composed primarily of chert and limestone. Due to the solubility of the limestones, these rocks are prone to karstification, forming features such as caves, sinkholes, and springs. Differential erosion of the limestone below the more resistant chert has resulted in the formation of the waterfall.

Considering that Natural Falls State Park is named after one of the largest waterfalls in Oklahoma, a prominent geologic feature, little geologic work has been done there. The most detailed mapping of the area is at a scale of 1:250,000 and occurred almost half a century ago (Marcher and Bingham, 1971). Thus, the area would benefit from more detailed surface mapping. Additionally, because much of the Boone Formation is lithologically similar, a biostratigraphic study would be important to place the rocks in the correct formation within the Boone Formation.

ACKNOWLEDGMENTS

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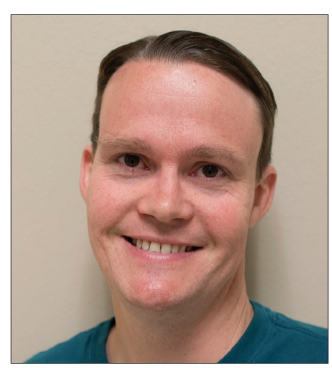
About the Authors

Julie Chang began working at the Oklahoma Geological Survey as a Geologist in 2008, making geological maps as part of the STATEMAP program, and most recently served as the geology group team leader until she left the OGS in June of 2018. She has three degrees in geology: (1) a Bachelor's from Montana State University, where she studied igneous rocks of the Absaroka Mountains, WY; (2) a Master's from the University of Arizona, where she studied mineralization related to alkaline igneous rocks in eastern Mexico; and (3) a Ph.D. from the University of Texas at El Paso, where she studied xenoliths within the Rio Grande Rift and igneous and metamorphic rocks of the Coast Range of western British Columbia. Her love of the outdoors and physical activity led her to pursue a career in the geosciences.

Stacey Evans joined the Oklahoma Geological Survey as a Research Geologist in late 2014. Her primary focus is field mapping. She is currently involved in the STATEMAP project updating the geologic map of Oklahoma. Prior to joining the OGS, she gained experience as a petroleum geologist working in the Anadarko Basin, the Permian Basin, and the Gulf of Mexico shelf. Other professional interests include sedimentology, diagenesis, and paleomagnetism. Stacey received both a B.S. (2008) and an M.S. (2011) in Geology from the University of Oklahoma. During that time she did field work in Nevada, Colorado, Missouri, Wyoming, and Scotland. Stacey currently sits on the OGS's Social Media committee and the Workshop and Fieldtrip committee. She is a member of the American Association of Petroleum Geologists, Geological Society of America, and the Oklahoma City Geological Society.

Russell Standridge has been with OGS since 2000 as a GIS Specialist. He got his start at OGS mapping earthquakes at the Leonard Geophysical Observatory. His duties as a GIS Specialist consist of cartography, geodatabases, spatial analysis, and publication maps and graphics. His current key projects and interests include geologic mapping for the STATEMAP program and Roadside Geology of Oklahoma. He has a B.A. in Applied Geography from Northeastern State University of Oklahoma and an M.A. in Geography from The University of Oklahoma.



BLOSSM in Oklahoma

WHAT IS BLOSSM?

The BLOSSM in Oklahoma project (Bridging Local Outreach & Seismic Signal Monitoring) aims to provide educational resources to public schools and free-choice learning environments, to foster scientific literacy, and to develop a community of citizen-scientists.

We plan to distribute 100 Raspberry Shake seismographs throughout the state in a three-phased deployment plan, and conduct professional development workshops for teachers during the Regional and Statewide Rollouts. Data collected from these seismographs are freely available to the public, and also supplement the Oklahoma Geological Survey (OGS) statewide seismic monitoring network in regions of the state where coverage is sparse.

WHAT IS A RASPBERRY SHAKE?

A Raspberry Shake seismograph is made up of (1) a geophone sensor that detects weak vibrations, (2) a circuit board that collects the data that the sensor detects, and (3) a Raspberry Pi mini-computer.

It is an all-in-one personal seismograph that can detect vibrations from earthquakes, even ones that are not normally felt by people. It works the same way as conventional seismic monitoring equipment, but at a small fraction of the cost.

WHERE WILL THEY BE DEPLOYED?

Some of our pilot sites will serve as regional hubs, where we will conduct professional development workshops for teachers who are interested in acquiring a seismograph to use in their classrooms. We will work with teachers to develop curricula that align with the Oklahoma Academic Science Standards.

HOW DO I GET A RASPBERRY SHAKE?

If you're interested in becoming involved, please contact us to see if you qualify for a free Raspberry Shake seismograph, provided by the BLOSSM in Oklahoma project. Alternatively, you may shop the manufacturer's online store directly, by scanning the QR code; please be sure to mention the OGS in the Order Notes when checking out.

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WHAT IF I HAVE MORE QUESTIONS?

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Unconventional Fossil Fuels Nomenclature

R.L. KLEINBERG
Columbia University Center on Global Energy Policy
Boston University Institute for Sustainable Energy

J. BOAK
Director, Oklahoma Geological Survey

The new fossil fuel resources that have emerged in the last few years — shale gas and tight oil — are unified not by resource type or by geology, but by a technology: massive staged hydraulic fracturing of horizontal boreholes. Massive fracturing is defined by the amount of rock surface brought into contact with a borehole drilled into the earth. In order to produce at economically viable rates, shale gas and tight oil wells must be exposed to about one million square meters or more of hydrocarbon-bearing rock (Vincent, 2012). The same equipment and technique is used for both resources (King, 2014). While fracturing rock for the purpose of enhancing production of oil or gas has been in use since the 1940s, it was generally employed at small scale, to create one fracture or a few fractures in a well. The drilling of long horizontal wells began seriously in the 1980s, but it was not until the new millennium that the possibilities of massive multi-stage fracturing of horizontal wells became clear, and technology was improved sufficiently to implement it.

Although the new resources are united by a production technique, their designations have adopted the paradigm of geologically-based terminology. Consequently, the naming of the various unconventional fossil fuel resources has suffered from a lack of coherence between and even within geological, commercial, financial, and media communities.

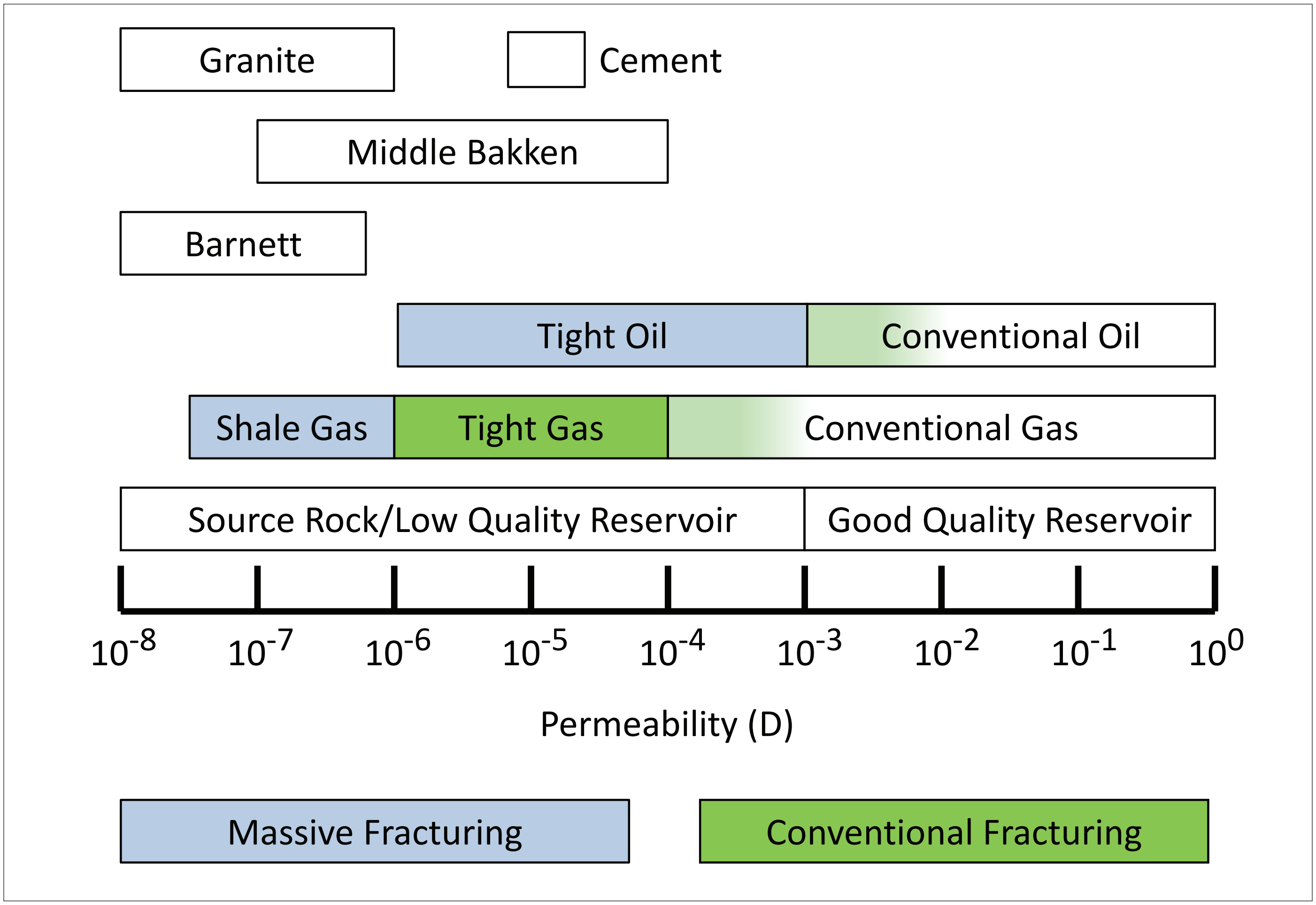

Figure 1. Nomenclature for oil and gas resources, plotted against rock hydraulic permeability. Barnett is a typical gas shale. Middle Bakken is a typical tight oil rock

Figure 1 is a nomenclature diagram. The horizontal axis is permeability, the ease with which fluids flow through porous rock (Hearst et al., 2000; Aguilera, 2013). The practical unit of permeability is the Darcy (1 D ~ $1x10^{-12}$ m^2). Other choices are possible, but permeability of the host rock relates most directly to the choice of production technique. The bars immediately above the scale show the approximate permeability ranges of the two principal rock types related to unconventional oil and gas: source rock and reservoir rock. The middle bars illustrate the spectra of gas and oil resources. Because the flow of fluids in porous media is proportional to rock permeability divided by fluid viscosity, and because the viscosity of light oil (usually about 1 centipoise) is about a hundred times larger than the viscosity of gas at reservoir conditions, gas resources can be produced from lower permeability rock.

ROCK TYPES

Shale is used ubiquitously to describe a diversity of newly exploited unconventional resources, but this is largely a misnomer. Within the geology and petroleum engineering communities, shale has three meanings: (1) rock containing a high proportion of clay minerals (Ellis, 1987); (2) rock comprising very fine grain minerals of any mineralogy (Lewan, 1978); (3) rock that is fissile — cleaving along bedding planes (Pettijohn, 1975). These definitions sometimes overlap.

From a mineralogical point of view,

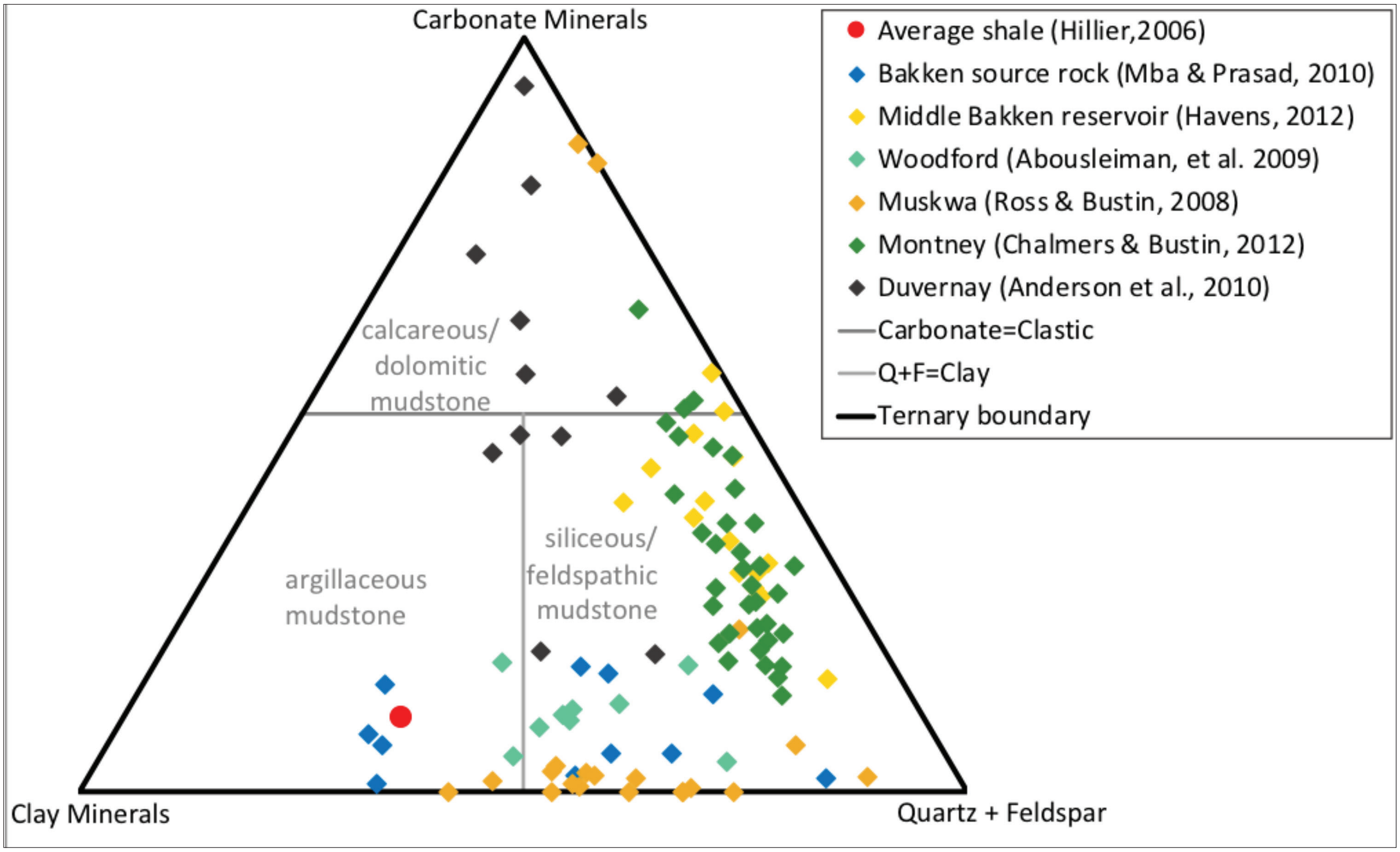

Figure 2. Mineralogy of North American unconventional oil and gas plays. Individual plays show considerable compositional variability. Sectors are descriptive of fine-grained rocks.

unconventional oil and gas resources are highly diverse. Figure 2 shows that North American "shale" plays have little in common with geologists' notion of shale, mineralogically defined. Only Bakken source rock comes close to the average shale shown, and that rock is not oil productive. Neither do these rocks consistently display the cleavage properties associated with shales as defined by their mechanical properties.

Many in the geological community advocate banishing the word shale from resource descriptors, preferring the term **mudstone** (Macquaker & Adams, 2003), which unambiguously refers to the fine-grained materials in which the new oil and gas resources are found. Unfortunately, shale seems to be firmly embedded in the discourses within and between the commercial, financial and media communities, and therefore will be hard to uproot.

Source rock is a particular kind of mudstone in which organic matter was co-deposited with inorganic minerals (Tissot and Welte, 2012; Sorkhabi, 2016). Upon being heated within the earth, it is the source of hydrocarbons. The presence of solid (or nanoporous) organic matter (kerogen) clogging what would otherwise be fluid-filled pore space makes source rock permeability very low. For this reason, source rock was considered hydrocarbon-nonproductive until the advent of massive hydraulic fracturing showed that gas — and sometimes oil — can be produced from it.

Reservoir rock describes formations into which conventional oil and gas migrate from source rock and is the formation type from which oil and gas have been produced for the last century and a half. It is both porous and permeable, though it ranges widely in quality, as illustrated by Figure 1. As technology has advanced, lower quality reservoir rock has been made productive. Conventional low-intensity fracturing is adequate to make low quality reservoir rock gas-productive and to make intermediate quality reservoir rock oil-productive. Fracturing does not necessarily improve the productivity of better quality reservoir rock: fracture fluids readily imbibe into this rock, moderating the build-up of borehole pressure so fractures do not propagate.

Tight Gas Sand is a low quality reservoir rock with permeability in the range 10^{-6} to 10^{-4} Darcy (Holditch, 2006). It is gas-productive either through natural fractures or is rendered productive by low-intensity conventional fracturing.

Gas shale is a generic term for formations that are gas-productive following massive hydraulic fracturing. They are more properly termed gassy mudstones and, because gas shales are almost always associated with kerogen, they can also be called gassy source rock.

Oil shale is a term used to describe source rock that has not yet gone through the oil window (Boak and Kleinberg, 2016). The terminology can be confusing because oil shale is commonly not a shale, and it never contains oil. Rather, it produces oil upon heating under appropriate conditions; the English language does not differentiate between containing and producing, as is evident from the common term wine grape. The term oil shale has been defined consistently since the middle of the 19th century, and remains in use to this day (OED, 1989a). Oil shale is frequently confused with formations that produce oil by massive hydraulic fracturing, in (false) analogy to gas shale.

RESOURCE TYPES

Tight gas is produced from low quality reservoir rock having a permeability of less than 10^{-4} Darcy. Tight gas is extracted from naturally fractured reservoirs, or by low-intensity conventional fracturing (Holditch, 2006).

Shale gas is the gas produced from gas shales (gassy mudstones) by massive hydraulic fracturing.

Associated gas is gas co-produced with oil, irrespective of source.

Tight oil has become the term of choice to describe oil produced by massive hydraulic fracturing. This terminology is sensible because tight oil is most commonly produced from low quality reservoir rock and is therefore geologically analogous to tight gas. The word tight is an abbreviation for tight rock, because the rocks are mineralogically and sedimentologically diverse, but consistently low in permeability. This terminology has been accepted by the World Energy Council (WEC, 2013), the US Energy Information Administration (EIA, 2018), the International Energy Agency (IEA, 2017), and the Organization of Petroleum Exporting Countries (OPEC, 2017).

Shale oil describes the product obtained by artificial maturation of oil shale by pyrolysis; this definition is more than a century and a half old (OED, 1989b). Unfortunately, even some who are aware of the traditional meaning of the term use shale oil to describe the fruit of massive hydraulic fracturing, in analogy with shale gas. This analogy is geologically false because shale gas is produced from rock with much lower permeability than the host rock of tight oil.

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Robert L. Kleinberg is a senior research scholar at the Center on Global Energy Policy of Columbia University and a senior fellow of the Institute for Sustainable Energy at Boston University. Dr. Kleinberg was educated at the University of California, Berkeley (B.S. Chemistry, 1971) and the University of California, San Diego (Ph.D. Physics, 1978). From 1978 to 1980 he was a post-doctoral fellow at the Exxon Corporate Research Laboratory in Linden, New Jersey. From 1980 to 2018 he was employed by Schlumberger, attaining the rank of Schlumberger Fellow. Dr. Kleinberg's work at Schlumberger focused on geophysical measurements and the characterization and delineation of unconventional fossil fuel resources. His current work centers on energy technology and economics, and on environmental issues connected with oil and gas development.

Dr. Jeremy Boak started as the Director of the Oklahoma Geological Survey in July 2015. Before coming to Oklahoma, he was Director of the Center for Oil Shale Technology and Research at the Colorado School of Mines and Chair of the Oil Shale Symposia from 2006-2015. Dr. Boak worked at Los Alamos National Laboratory as a project manager in environmental management, pollution prevention and nuclear materials disposition and at the U. S. Department of Energy (DOE) Yucca Mountain Project leading performance Assessment. He also worked as an exploration geologist at ARCO Inc. He has a B.A., M. S., and Ph. D. from Harvard University, and an M.S. from the University of Washington, all in Geological Sciences.

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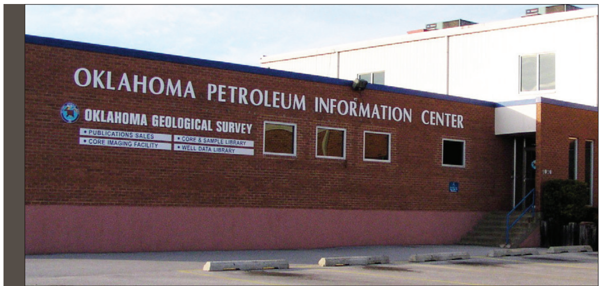

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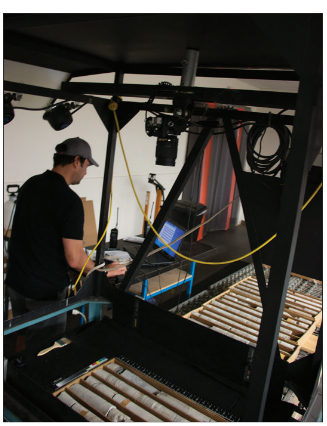

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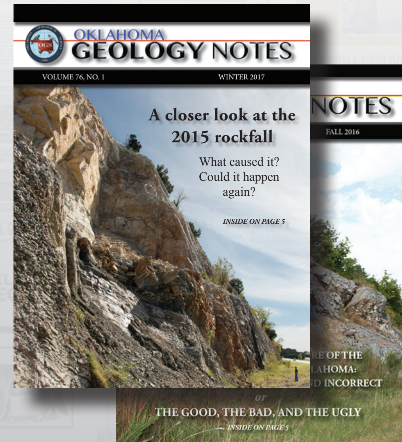

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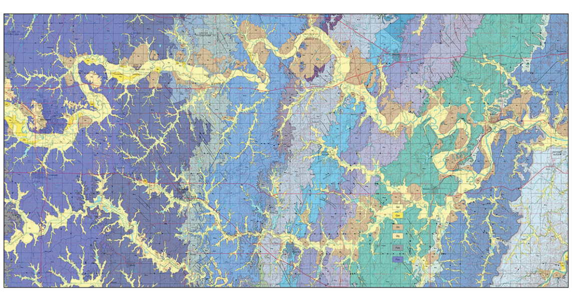

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