Geology of Lee County, Iowa

and Its Aquifers

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Geology of Iowa

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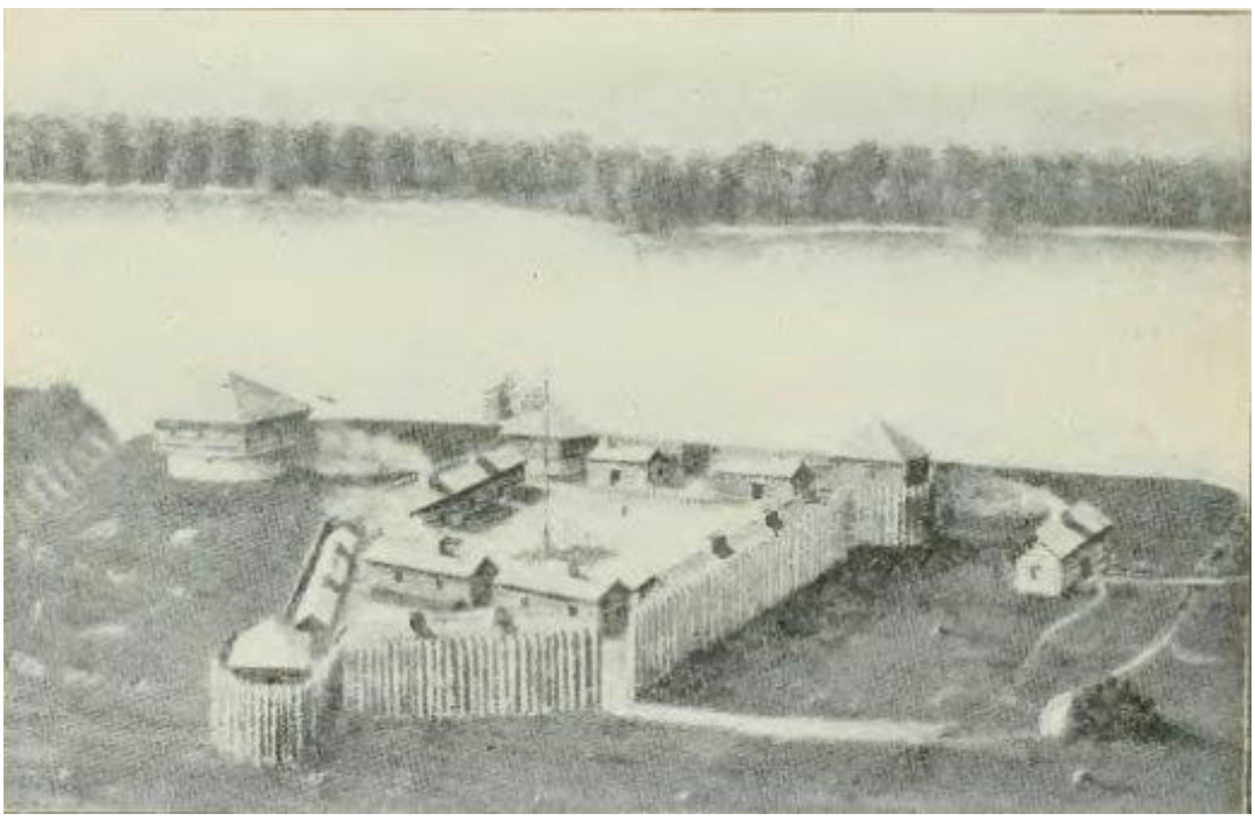

Artist depiction of Old Fort Madison along the Mississippi River back in 1808. (Gue 1903)

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Abstract

The geology of Lee County, Iowa, has a long and varied history. Depositional environments make transitions through cooling magma into igneous rock, into a long extended period of transgressive-regressive seas, then to a partial swampland, ending finally with glacial stages depositing massive amounts of till across the county. These depositional environments were the determining factor into what the composition of the formations would be, and therefore if they would be water-bearing or not. Rocks with the highest porosity will yield the most water compared to rocks with low porosity. Depth and thickness of these formations also plays a role in how much water would be yielded from wells dug into the buried rock. The thicker the aquifer, the more water it holds and the greater its yield. Surficial geology, which contains unconsolidated sediments like the glacial till, follows similar patterns as the consolidated rock for forming aquifers. The more pore space and thickness the loose sediment has the more water it can yield. All these things are analyzed to show the best and most widely used aquifers in Lee County, Iowa.

Introduction to Lee County

Lee County, Iowa is located in the southeastern most corner of the state (Figure 1). Geographically, Lee County is bordered by the Mississippi River to the East, the Des Moines River to the South, Van Buren County to the West, and part of the northern edge is bounded by Henry County and the other part is bounded by the Skunk River. Of this boundary, almost 75 percent of it is rivers. The county has a total area of 539 square miles, with 518 of that being land and the other 21 square miles being water, according to the U. S. Census Bureau. The county is home to the state's lowest geographic point. This point is located in the city of Keokuk at the southernmost tip of Iowa, where the Mississippi River finishes flowing past Iowa (Figure 2). The county has two prominent waterways besides the mighty Mississippi, the Skunk River and the Des Moines River. These two rivers are the drainage points for the county's two watersheds, each named after the rivers. The only part of the county that drains into the Skunk River is located in the northeastern corner up next to the river. The rest drains to the Des Moines River to the south. Besides these sources of surface water, Lee County contains several aquifers that many industries, businesses, and residents rely on for their water supply. Because of this, the geology of Lee County plays an important role in the county's need for water, whether it is from these deep underground aquifers or from the surface features perfectly exemplified as the many rivers surrounding the county.

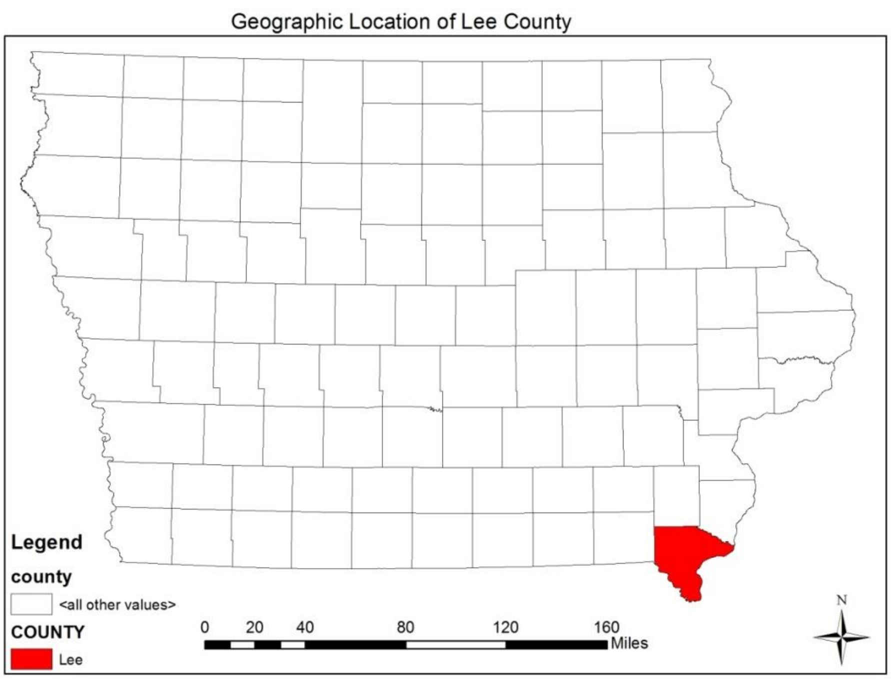

Figure 1 Map showing the geographic location of Lee County in the state of Iowa.

The history of Lee County begins with its first known settlement by a people known as the mound builders. Not much is known about these people besides the mounds they have built at Green Bay Bottoms near the township of Wever in the northeast corner of the county. All that is known comes from the few relics, such as stone axes, flints, arrowheads and pottery chunks that have been found. The county was then populated by the Fox and Sac tribes of the Algonquin family, which were first encountered by white man in 1673. This first encounter in 1673 was recorded by Father Marquette, who met these Natives Americans along the stretch of the Des Moines River which is now Lee County's southern border (Parker 1942). After the county's discovery by Europeans, a settlement of theirs was not completed until 1809. This settlement was created by a U. S. garrison under the command of Lieutenant Kingsley. The settlement was a fort meant to protect the area from local Native American attacks. Once it was completed on April 14, 1809, the fort was named Fort Madison after the fourth president of the United States, James Madison, and became the roots for Lee County's oldest settlement.

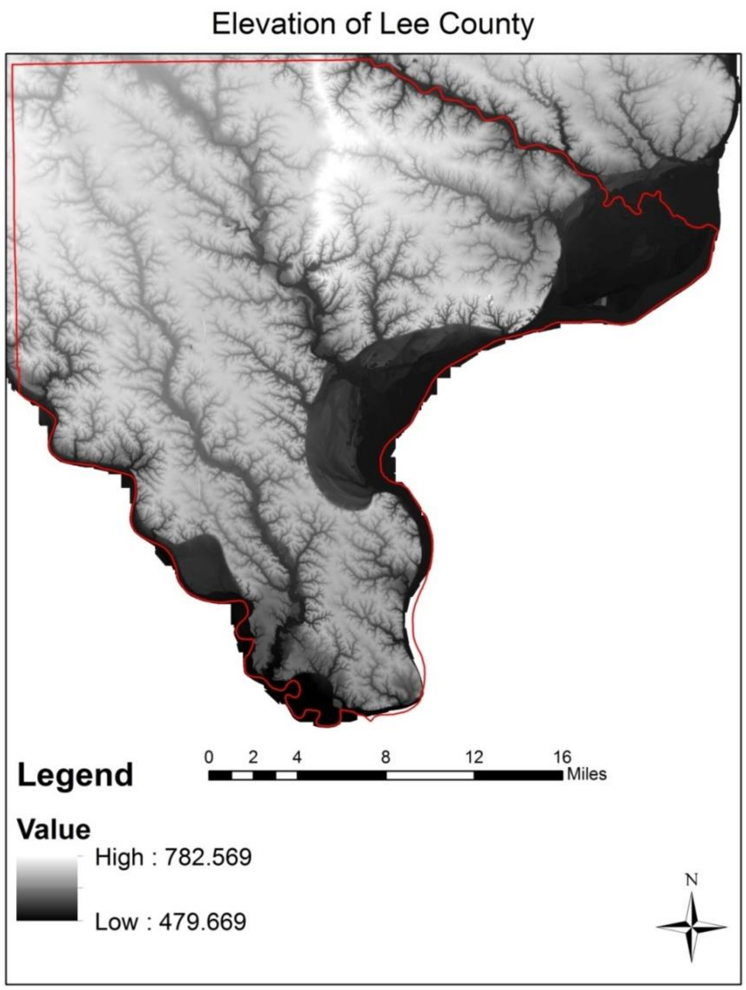

Figure 2 Map showing the elevation of Lee County above sea level.

Lee County was officially given its title on January 23, 1839 by the Iowa Territorial Legislature (Parker 1942). There is debate on where exactly the name of Lee came from. Some believe that it was named after Robert E. Lee, the commander of the Confederate Army, who surveyed the area where the Des Moines River meets the Mississippi. It is assumed though, that it was originally named Lea after Lieutenant Albert M. Lea in 1835 who surveyed most of Iowa and Minnesota, but a clerical transcribing error accidentally changed it to Lee. Therefore, when the county was officially named it was given the title Lee instead of the initial name of Lea.

Modern day Lee County now contains eight official cities as seen in Figure 3. As of the 2010 census the recorded population of the entire county was 35,862 with a population density of 69.3 people per square mile. Of the population, race distribution is 93.5 percent white and 3.1 percent African American with 3.4 percent other. Age distribution is consistent for all age groups except 18-24, and 65 and older; which are lower than the 25 percent average of 45-64, 25-44, and 18 and younger groups.

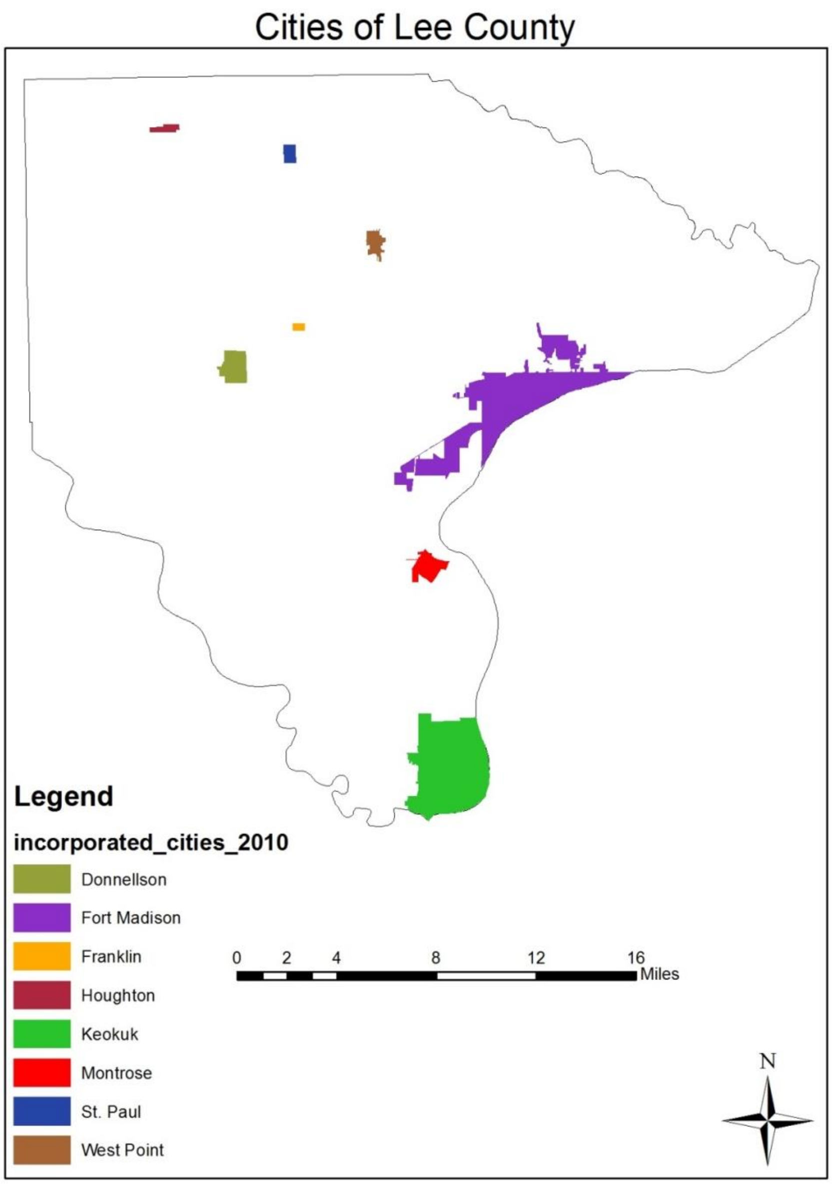

Figure 3 Map showing size and location of Lee County's incorporated cities as of 2010.

The majority of this population is located in the county’s two largest cities, Fort Madison and Keokuk. These two cities are some of Iowa’s oldest settlements. Fort Madison’s origins were stated above, and during the War of 1812, the fort was attacked and abandoned. After the war ended, settlers came and established a community around the ruins of the old fort that had been destroyed in the war. The city was officially incorporated in 1895. Keokuk is Lee County’s second oldest settlement and is one of Iowa’s oldest cities. The second largest city in Lee County, Keokuk was first settled in 1820 by Dr. Samuel C. Muir (Parker 1942). Instead of Keokuk, he called it “The Point”, since he settled on the bluff overlooking the convergence of the Mississippi and Des Moines River. The settlement was first called Keokuk by Colonel George Davenport after the Sac Indian chief Keokuk. The settlers were hesitant to accept the name change from “The Point” to Keokuk, but they agreed after friendly persuasion by Davenport. The settlement continued to grow, and in late 1848 the city was officially incorporated.

Geologically, Lee County is very important when it comes to classifying carboniferous limestones. Due to the prominent exposures of the Keokuk Formation of limestone at Keokuk, Lee County was used as a starting point for classification of various limestone formations throughout the Mississippi Basin (Keyes 1893). These limestones formations also allowed for Lee County to have limestone as one of its major natural resources. Back in the 1890s, Lee County was also a producer of coal with 15 total mines, but all were closed before the 1900s. Another important natural resource is the groundwater found throughout the county’s underlying rock. The final natural resource Lee County has is electrical energy from its powerhouse and dam.

The powerhouse and dam in Lee County is located next to the city of Keokuk along the Mississippi River before it converges with the Des Moines River. Known as Lock and Dam No. 19, the building of the dam was first contracted by the Mississippi River Power Company in 1901 (Parker 1942). Construction of the lock and dam began in 1910 and was completed in 1913, and at that time the power house was largest capacity, electricity generating plant in the world. Power generated from the dam was and still is sent down and used in St. Louis.

Before construction of the dam, the Des Moines Rapids, the area where the Mississippi River and Des Moines River collide, prevented any river traffic from continuing up the Mississippi due to shallow water depths of less than five feet. The building of the dam greatly increased water depth and removed these rapids, allowing for river traffic to continue upstream. This altering of the river greatly impacted the lands upstream, due to the creation of the reservoir pool behind dam. Originally, the land now covered by the reservoir pool was a low and marshy bayou with very sandy river banks. These low lands were at one point cleared and used as some of the most fertile farmland in the state, but the reservoir completely inundated them and covered most of the remaining lowland and bayou areas. Along with these lowlands, the reservoir also changed the entire topography of the Mississippi Valley for tens of miles upstream all the way up to Burlington, Iowa. This also caused inundating hundreds of islands, a few villages along the banks, and even half of the city of Montrose in Lee County. The Mississippi River Power Company did buy out all of the flooded land before construction, but this flooding greatly angered local farmers who just lost some of their most fertile land. Over all the dam caused an increase in upstream river width by three-fourths of a mile up to three miles and condemned nearly 25,000 acres of farmland (Parker 1942). This change greatly impacted the local geology along the river, and created the land area of Lee County now seen (Figure 4).

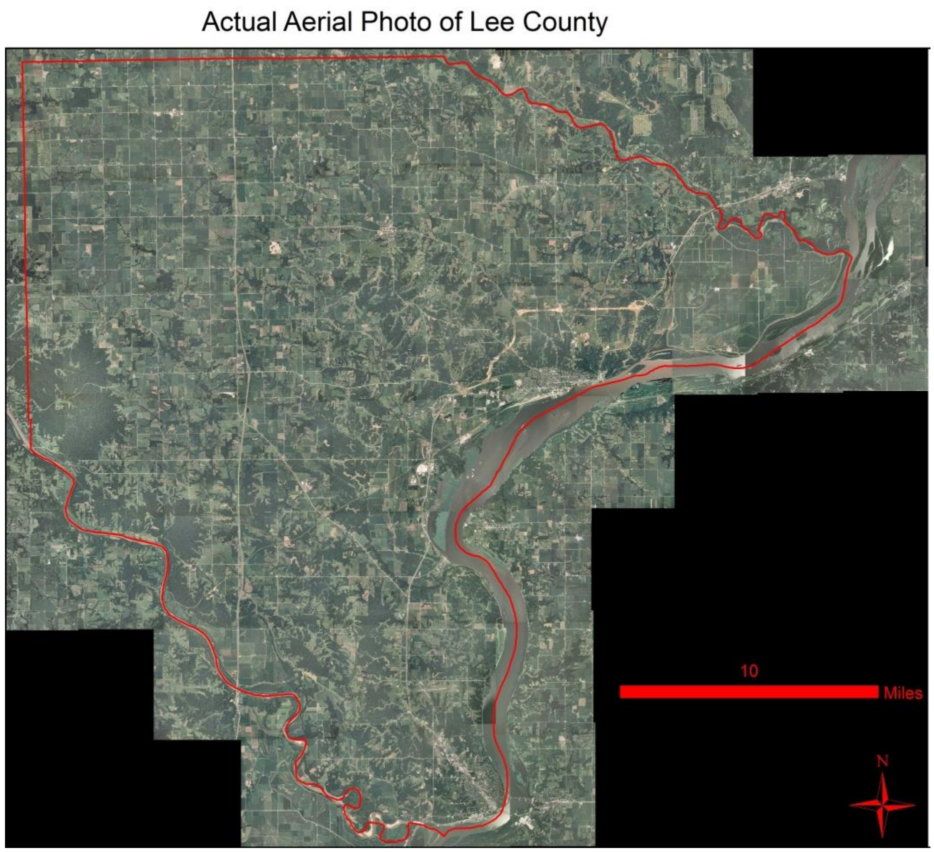

Figure 4 Aerial photo of Lee County in 2010.

Overview of Iowa's Bedrock Geology

Iowa's rock record contains rock spanning almost all of geologic time. Only six major unconformities in the rock record of Iowa occur. These unconformities make up the only time span in Iowa when no new rocks formed. The first of these occurs at the base of the Cambrian. The next occurs within the Ordovician, followed by and unconformity at the base of the Devonian. These three are relatively small unconformities compared to the next two unconformities. The smaller of these two being between the Mississippian and the Pennsylvanian. This is followed by the largest unconformity that loses two periods, the Permian and Triassic, in the rock record. The final unconformity lies between the Jurassic and Cretaceous. Besides these six unconformities, Iowa contains a relatively continuous rock record whose bedrock locations throughout the state can be seen in Figure 5.

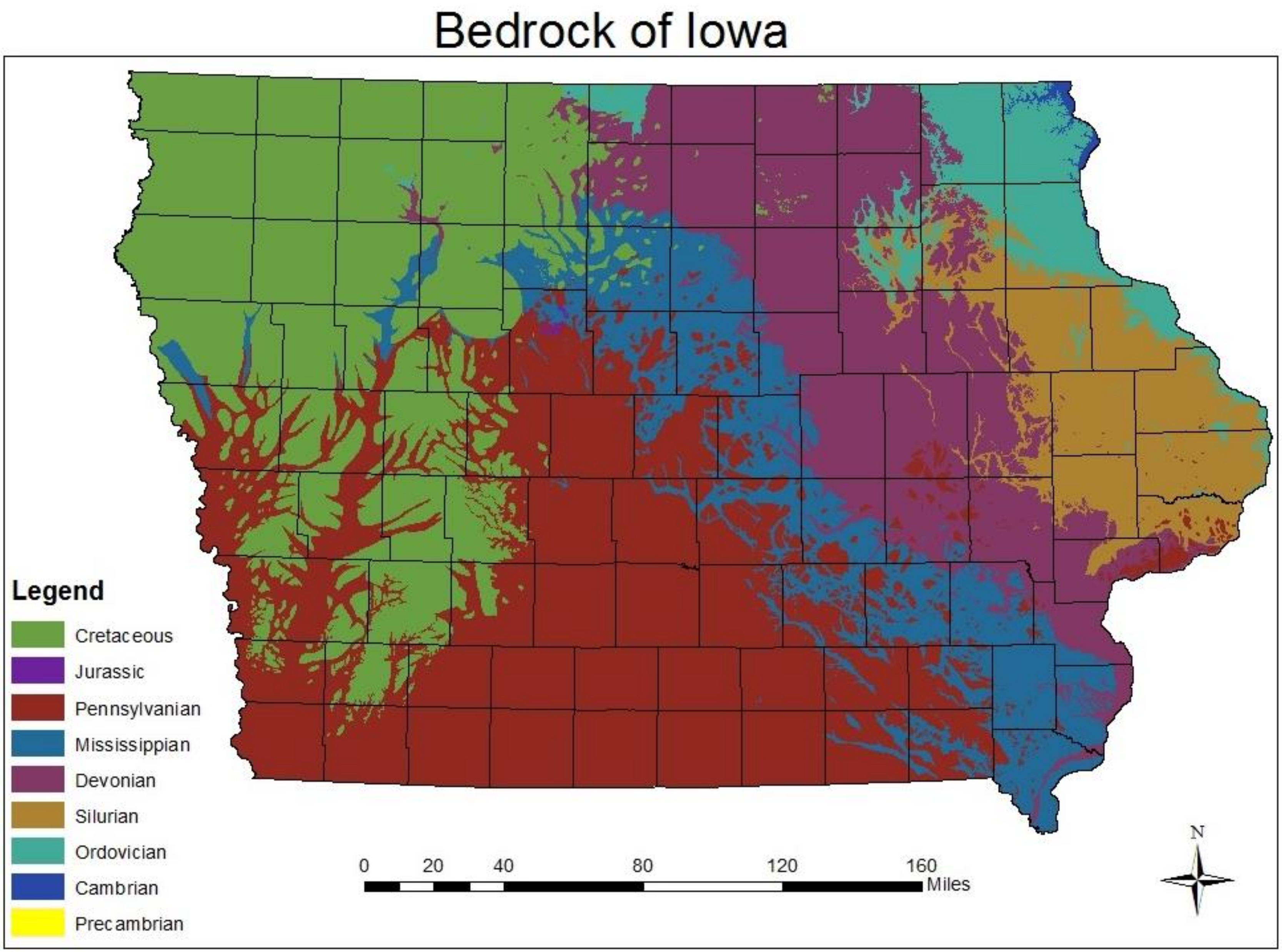

Figure 5 Distribution of bedrock of Iowa.

This rock record begins with the Precambrian almost three billion years ago. This supereon starts with the formation of igneous and metamorphic rock, transitioning into various mountain building events. This resulted in the formation of various Precambrian rocks such as the Eastern Granit-Rhyolite Province, the Central Plains Orogenies, and the Penokean Orogen. Today, the only exposed rock from this period is located in the northwestern corner of Iowa in the Gitchi Manitou State Preserve. Called the Sioux Quartzite, this metamorphic rock was created over 1.6 billion years ago. Then 600 million years after this quartzite was created or one billion years ago, North America was almost torn apart by the Midcontinent Rift System. The Midcontinent Rift System spans from the southwest corner of Iowa through the northern and northeast part of Iowa and up to Wisconsin, Minnesota, and Lake Superior. This event produced various mafic minerals right at the rift area, including both extrusive basalts and intrusive gabbros. Near the edges of this rift, sediments accumulated to form various clastic sedimentary rocks. No fossils are found in Iowa from this period due to the small variations in life and rather extreme conditions during this period. It is not until the Cambrian period till fossils become more prevalent.

The Precambrian made a transition into the Cambrian around 541 million years ago. Looking at Iowa's rock record from various drill cores, it can be seen that there are no rocks from this transitional Early Cambrian time. Because of this, it is believed that during this transition time, Iowa was above sea level and undergoing weathering and erosion, forming an unconformity in the rock record. As time passed into the Late Cambrian, a shallow sea encroached and flooded Iowa with marine waters. This sea fluctuated in height leaving behind a rock record of shore, inner-shelf, and offshore-shelf deposits. These deposits are divided up into six formations in Iowa, which are known from oldest to youngest as Mt. Simon, Eau Claire, Wonewoc, Lone Rock, St. Lawrence, and Jordan. These deposits can be seen as quartz sandstones, shale, dolomite, or a mix of the three. Out of these, the Jordan and St. Lawrence are the most popular due to their composition as mature sandstone, which makes them an excellent aquifer for many cities and industries in Iowa. These formations can be found near Lansing, Iowa, and Effigy Mounds National Monument respectively. Even though this period of time experienced an explosion of life, Iowa's Cambrian rocks hold very few fossils. This is mainly because fossils are poorly preserved in the sandy shorelines and inner shelf regions that Iowa experienced during this time, but this will change as the Cambrian ends and the Ordovician begins.

At 485 million years ago, the Cambrian ends, and the Ordovician begins. Like the Late Cambrian, the Early Ordovician of Iowa experienced a shallow inland sea that fluctuated leaving behind more carbonate rock and quartz sandstone. As the Early Ordovician came to an end, the shallow sea regressed and exposed the rock in Iowa to weathering, which again caused an unconformity in the rock record. When the Middle Ordovician began, the sea transgressed back onto Iowa depositing extremely mature quartz sandstones. Continuing on into the Late Ordovician, the sea continued to transgress and changed Iowa from a shallow sea floor environment to a muddy carbonate shelf. Of these environments, five formations have been determined in Iowa. They are from oldest to youngest the Prairie du Chien, St. Peter, Platteville, Galena, and Maquoketa. The Prairie du Chien, found in Yellow River Sate Forest, was deposited during the Early Ordovician and is composed mainly of dolomite. Then after the period of unconformity, the St. Peter sandstone was deposited, which can be seen today in Pikes Peak State Park located in northeast Iowa. The rest of the formations were deposited during the Late Ordovician and are respectively composed of limestone, dolomite with chert, and shale. As for fossils, algal mats and masses remains are easily visible in the Prairie du Chien Formation, but like the Cambrian the sandy St. Peter Formation has hardly any. As for the Late Ordovician time, a variety of fossils such as cephalopods, gastropods, brachiopods, and trilobites are well preserved in the dolomite and shales.

The Ordovician ends with another major sea regression and erosion period, leaving a massive unconformity between it and the Silurian which begins around 443 million years ago. After period of time, the sea transgressed back over part of Iowa and continued to deposit carbonates. During this period, the sea underwent five transgressive-regressive cycles that can be seen in the carbonate rock. In the Silurian, there are six dolomite formations and two limestone formations. They are with age Mosalem, Tete des Morts, Blanding, Hopkinton, Scotch Grove, and Gower as the dolomite formations and the limestone formations as Waucoma which is the same age as Hopkinton, and La Porte City which is aged same as Scotch Grove. The most prominent of these formations is the Hopkinton, which can best be seen in Maquoketa Caves State Park. Also in the Scotch Grove and Gower Formations, there are carbonate mounds, also called bioherms, which consist of fine grained dolomite with large colonial rugose corals, crinoid beds, and tabulate corals. Fossils are abundant and come in a large variety in the Silurian strata. The fossils include algae, corals, crinoids, brachiopods, and stromatoporoids. All which make up important parts in the carbonate mounds found in the Scotch Grove and Gower Formations.

Like the end of the Ordovician, the Devonian begins with a period of intense weathering and erosion, leaving a large unconformity at the base of the Devonian. The Devonian began around 419 million years ago, and had approximately 4 million years till the seas regressed and exposed the depositing rock to erosion. This lasted around 30 million years until Iowa’s resubmergence during the Middle Devonian, where Iowa’s Devonian rock begins. Iowa contains four groups with twelve total formations. The oldest group is the Wapsipinicon Group, which contains three formations Bertram, the oldest, Spillville-Otis, and Pinicon Ridge, the youngest. Next is the “Lower” Cedar Valley Group, containing the Little Cedar and Coralville Formations. This is followed by the “Upper” Cedar Valley Group with the Lithograph City and Shell Rock Formations. Finally, the “Yellow Spring” Group contains the youngest formations, the oldest of which is the Lime Creek Formation, and its lateral equivalent Sweetland Creek, followed by the Sheffield, Aplington, and Maple Mill Formations. All of these formations were deposited during several transgressive-regressive cycles that are recorded in the formations. Most of the lower formations consist of dolomite and/or limestone, while the upper formations in the “Yellow Spring” Group consist primarily of shale. In the calcareous rocks, fossils are extremely common. Various types of fossils can be found, like brachiopods, corals, crinoids, and stromatoporoids.

This can be seen in the Little Cedar Formation, which contains the most famous fossil outcrop in Iowa, the Devonian Fossil Gorge near Coralville, Iowa.

The Devonian makes a transition into the Mississippian around 358 million years ago. The conditions for the Mississippian are very similar to the Devonian with Iowa being covered by shallow seas and experiencing several transgressive-regressive cycles. The Mississippian is the last time period when Iowa is covered by a sea. It is divided up into four different series containing ten different formations. The oldest series is the Kinderhookian, which contains the McCraney, Prospect Hill, Starrs Cave and Wassonville Formations. Named by Meek and Worthen in 1861, the name refers to the strata between the black slate and the base of the Burlington limestone at Kinderhook, Pike County, Illinois (Van Tuyl 1922). Next is the Osagean Series with the Burlington, Keokuk, and Warsaw Formations. The Osagean Series is also known as the Augusta Series, where the two can be used interchangeably to refer to the same group of formations. Then the Meramecian Series follows with its two formations, the Salem (Spergen) and "St. Louis". Finally, the Chesterian Series is the youngest period containing the Pella Formation. These formations record 10 transgressive-regressive cycles and are primarily composed of calcareous rock mixed with chert and/or shale. Fossils are located within most formations, and these rocks have long been of interest to paleontologists for their quality of preservation. The most famous of these fossils are the crinoid beds and the rarely persevered starfish in southeastern Iowa, along with the important discovery of amphibian fossils. Other less famous fossils include brachiopods, mollusks, corals, fish parts, and conodonts.

As the seas retreat from Iowa at the end of the Mississippian, the rocks were subjected to uplift and erosion. This creates an unconformity between the Mississippian and soon to be deposited Pennsylvanian rocks. The Pennsylvanian begins around 298 million years ago and marks a new type of depositional environment in Iowa, which are alternating marine and nonmarine environments. Within the Pennsylvanian, there are five series with a total of ten groups or formations. The lower series is the Morrowan with the Caseyville Formation. Next is the Atokan Series, containing the Lower Cherokee Group. The Desmoinesian Series follows the Atokan with the Upper Cherokee and Marmation Groups. After that, the Missourian Series elapses with the deposition of the Bronson, Kansas City, and Lansing Groups. The final series is the Virgilian Series with the Douglas, Shawnee, and Wabaunsee Groups. These groups are composed mainly of limestone and shale with coal beds found within almost all groups. These deposits were formed by numerous fluctuations in sea level. During the nonmarine times, Iowa's environment was mainly that of coastal swamps and deltaic plains, which promoted the formation of coal deposits. As for marine times, the environment was the basic shallow seas. These environments allowed for the formation of various fossils. During the nonmarine times, scale trees (lycopods) and fern fossils can found, while during marine times brachiopods and calcareous algae are most prominent.

After the Pennsylvanian comes the Permian at the end of the Paleozoic. The Permian record along with the Triassic of the Mesozoic is not found in Iowa's rock record. This is due to a period of erosion that Iowa underwent during most of the Mesozoic era, which began around 232 million years ago. Of the rest of the Mesozoic, only a small part of the Jurassic record is found, consisting only of the Fort Dodge Formation. This formation is composed of primarily of gypsum with some red, green, and gray clastic rocks. It is believed that these rocks were deposited in restricted marine and nonmarine environments along the edge of an inland sea (Anderson 1998). The last part of the Mesozoic, the Cretaceous, is common in western and northwester Iowa. This consists of the Dakota Formation and its lateral equivalent, the Windrow Formation. Above this lies the Graneros Formation followed by the Greenhorn, Carlile, Niobrara, and Pierre Formations. The Dakota Formation is composed of mainly of sandstone and mudstone with some conglomerate, shale, and siltstone. The Graneros marks a transition with some mudstone and siltstone to more prominent shale composition for the Greenhorn, Carlile, Niobrara, and Pierre Formations. This implies an environment that transitioned from a coastal marine setting to a muddy marine shelf with low levels of oxygen in bottom waters. During the Late Cretaceous around 73.8 million years ago, a meteor approximately 1.2 miles in diameter slammed down just north of the city of Manson, Iowa. This impact created a crater now known as the Manson Impact Structure, which is one of the world's largest impact craters. The crater has since been filled in by deposited rock from the Cretaceous.

The final era of geologic time is the Cenozoic, which begins around 66 million years ago and continues into the present. This geologic time period saw very few rock deposits, but is the basis for all of Iowa's landforms. From 66 million years ago until 2.5 million years ago, Iowa was subject to wreathing and erosion, which resulted in very few Tertiary rock deposits. In this last 2.5 million years, Iowa endured several glaciation periods. This resulted in poorly sorted glacial drift being dumped all over Iowa, creating the base of Iowa's soils. The rest of Iowa's landforms came from windblown silts and other fine-grained sediments known as loess, and from alluvium which is clay, silt, sand, and gravel deposited in river valleys from the local river. These depositions took place is what is known as the Quaternary Period, which is divided up into the Pleistocene and the Holocene. Iowa has a vast Pleistocene record, which includes multiple Pre-Illinoian drifts from the Pre-Illinoian Glacial Stage, an Illinoian Stage, and two drifts from the Wisconsinan Glacial Stage. Also, two interglacial stages are recorded, the Yarmouthian and Sangamonian.

From these glacial and interglacial stages and extensive water flow across the surface of the state, ten distinct landform regions have been formed. These ten landform regions are the Des Moines Lobe, East-Central Iowa Drift Plain, Iowa-Cedar Lowland, Iowan Surface, Loess Hills, Mississippi River Alluvial Plain, Missouri River Alluvial Plain, Northwest Iowa Plains, Paleozoic Plateau, and Southern Iowa Drift Plain (Figure 6). Of these ten, three fall into the same overarching landform regions known as Alluvial Plains. These three are the Iowa-Cedar Lowland, the Mississippi River Alluvial Plain, and the Missouri River Alluvial Plain. With these three grouped together, Iowa can be seen to have eight types of landform regions versus ten distinct regions.

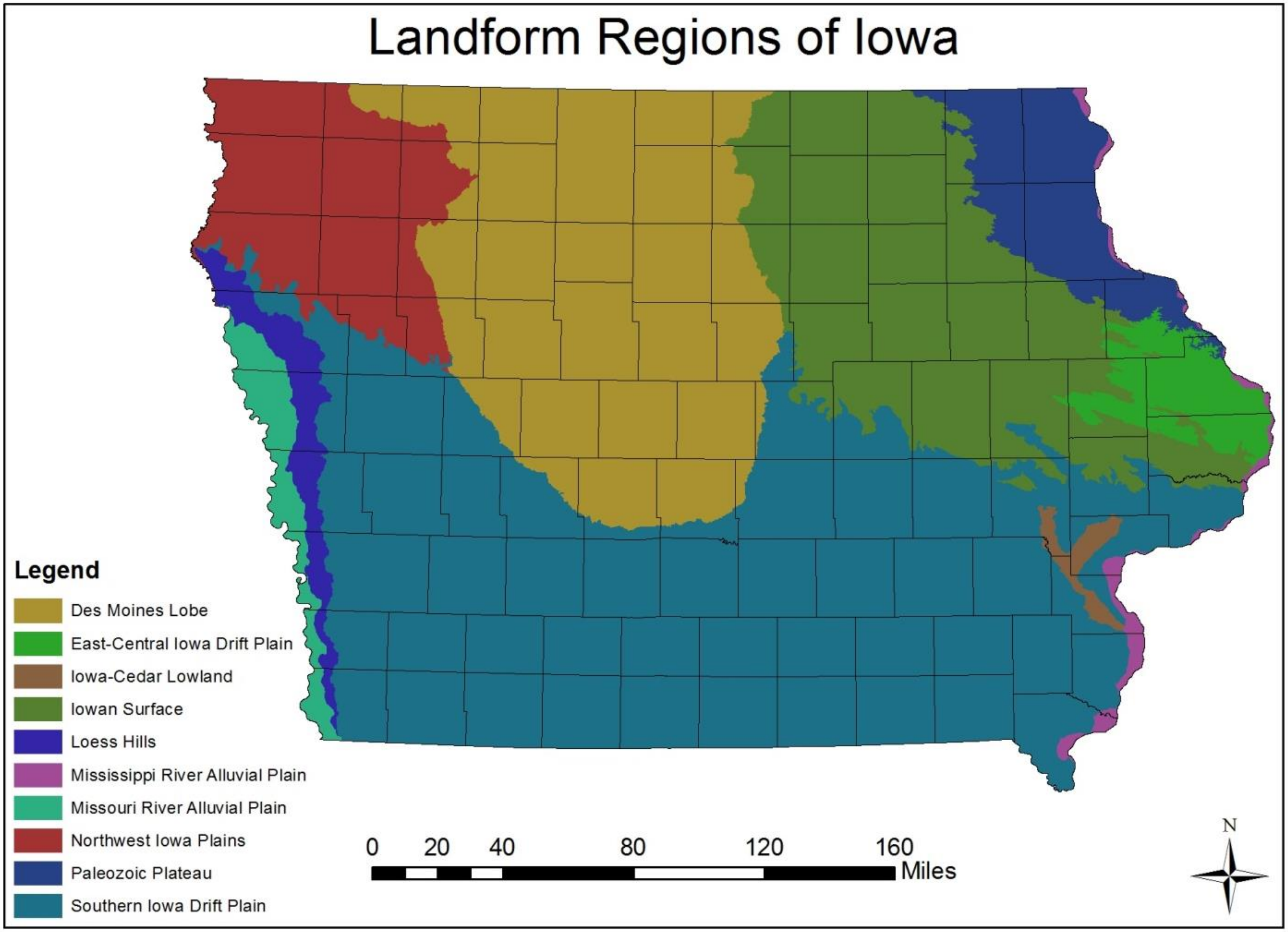

Figure 6 Landform Regions of Iowa

Overview of Iowa's Aquifers

Iowa contains two major aquifer systems and four major aquifers. An aquifer system is defined as two or more hydraulically connected aquifers that operate in a like manner in reaction to changes in hydrologic conditions (Olcott 1992). These aquifer systems and aquifers are in ascending order: the crystalline-rock aquifers, the Cambrian-Ordovician aquifer system, the Silurian-Devonian aquifer, the Mississippian aquifer, the Cretaceous aquifer, and the surficial aquifer system (Figure 7). These aquifers are extremely important to the state of Iowa. Back in 1992, 82 percent of the state's population relied on these groundwater resources for their freshwater (Olcott 1992). This value has not likely changed much in recent years, due the minimal accessibility to large, clean, above ground freshwater sources.

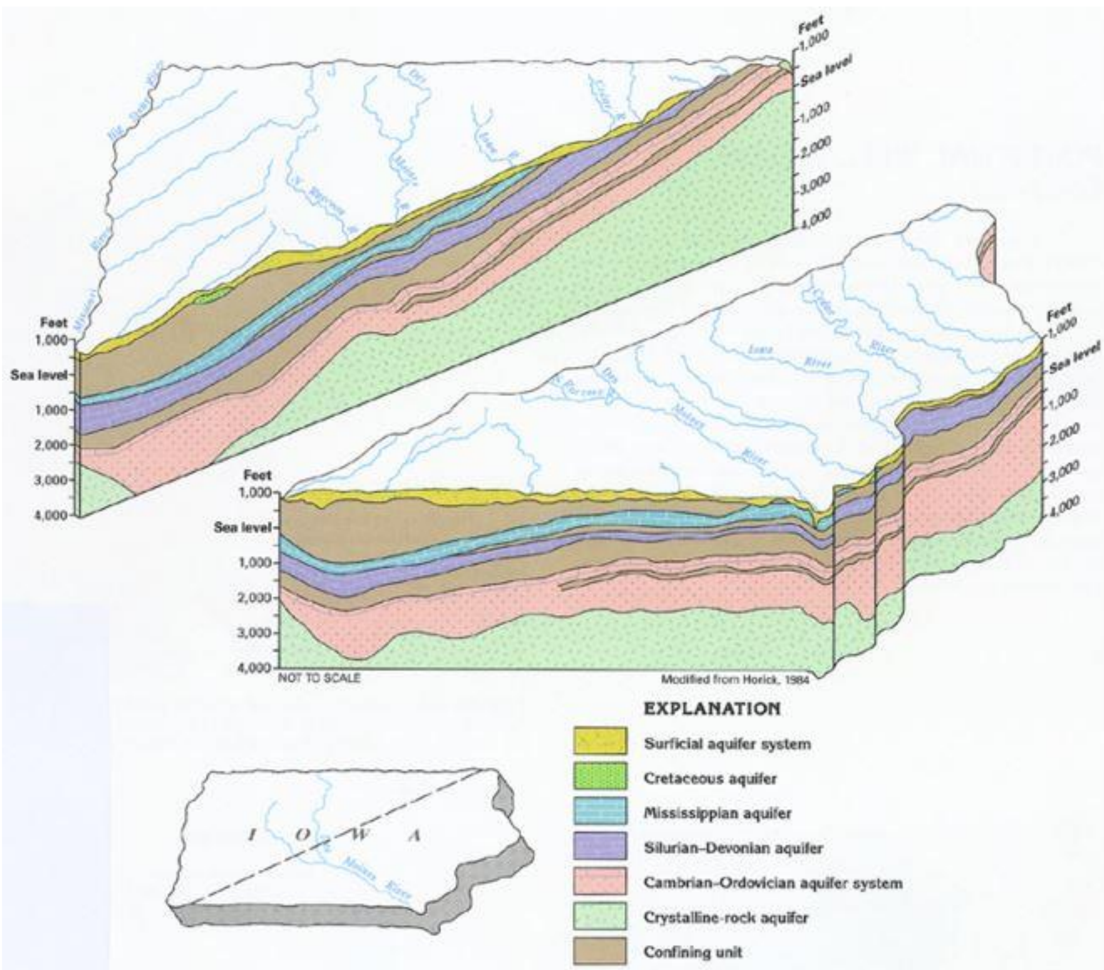

Figure 7 Cross-sectional map of Iowa's aquifers. From Olcott 1992.

For Iowa, very few places tap into the crystalline-rock aquifers. These aquifers are located within the Precambrian rock buried deep below Iowa. Normally, crystalline rocks act as a barrier to the flow of ground water, because of their lower permeability compared to the overlying sediments. It is possible though for water to move through secondary openings in the rocks, such as any joints or fractures that may have occurred in those rocks at one time. Unfortunately, these openings are irrelevant at any depths below a few hundred feet, resulting in minimal aquifer use in Iowa due to most Precambrian rock lying well below this depth (Olcott 1992). Because of this, it is relatively pointless for an entity to attempt to tap into it when instead a more accessible aquifer could be used. In some places though, such as northwestern Iowa, if no other aquifers are accessible, then these crystalline rocks act an important source of fresh water.

The Cambrian-Ordovician aquifer system is a more accessible and widely used aquifer system than the crystalline rock aquifers (Figure 8). This system is a complex multi-aquifer system made up of three principal aquifers that are separated by leaky confining layers. These aquifers and confining layers span all of the Cambrian and Ordovician rocks and are capped with the Ordovician's shaley Maquoketa Formation, which creates an impermeable layer to separate it from the next set of aquifers. These principal aquifers come about from the Cambrian and Ordovician's lithologies. They primarily consist of sandstone in the lower part and shift to sandstone and shale interbedded with calcareous rock in the upper part, which causes changes in the water-yielding characteristics of each rock (Olcott 1992). The aquifers and confining layers in ascending order are the Mount Simon Aquifer, the Eau Claire Confining Unit, Ironton-Galesville Aquifer, St. Lawrence-Franconia Confining Unit, St. Peter-Prairie du Chien-Jordan Aquifer, and the capping Maquoketa Confining Unit. Of these aquifers, the St. Peter-Prairie du Chien-Jordan Aquifer is the primarily used aquifer in Iowa. This is because the other two aquifers contain saltwater throughout most of the state, therefore making highly unfavorable for use.

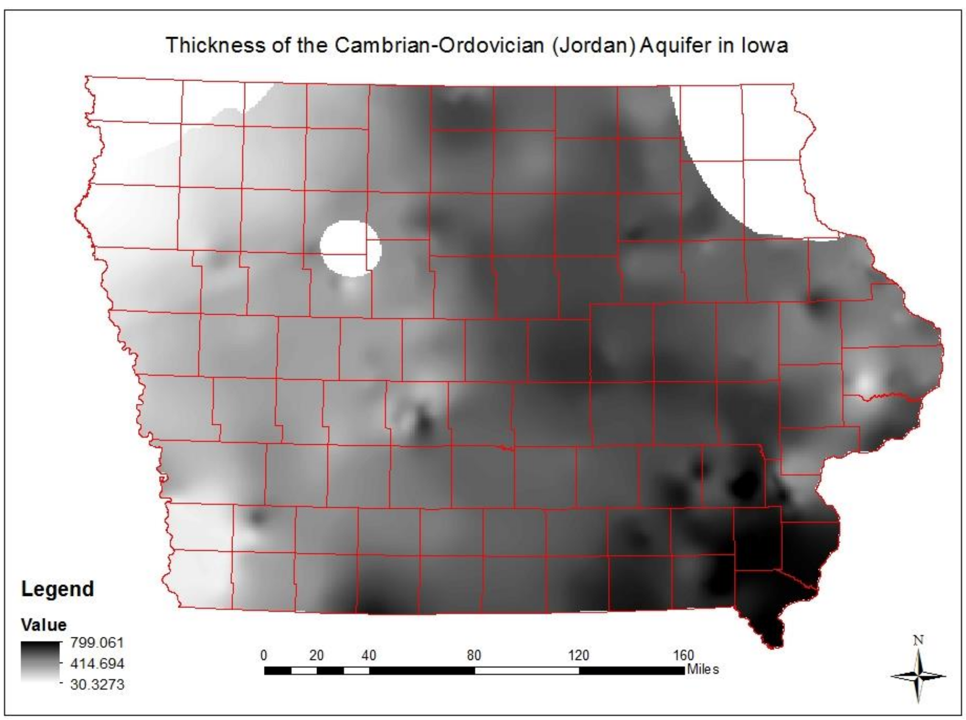

Figure 8 Thickness of the Cambrian-Ordovician Aquifer in Iowa.

The Silurian-Devonian aquifer is contained by 90 percent of the state with only the northeast corner not containing it (Olcott 1992). It spans all of the Silurian and Devonian rock with no confining layers until the “Yellow Spring” Group of the Devonian, whose shale layers confine the aquifer. The lithology of the aquifer is mainly carbonate rock throughout, but it can be interbedded with evaporate deposits and a few shale beds. Like that of crystalline rock, water primarily moves through secondary openings like joints and fractures that have been enlarged by dissolution of the carbonate rock. This primary way of movement allows water in the aquifer to move fastest where this dissolution is greatest. This leads to well yields being dependent on the degree of porosity created by this dissolution rather than the thickness of the rock, which is the major well yield factor for aquifers like sandstone (Olcott 1992). In Iowa, this dependence can be seen through the change in bedrock from the northeast to the southwest corner. The northeast part of Iowa sees rapid recharge in the aquifer due to increased porosity caused by the aquifer being bedrock. In the southwest, the aquifer is confined and has very slow recharge rates and poor ground water quality due to slow water movement within the aquifer. This means the aquifer is more extensively used in northeastern Iowa, and experiences less and less use toward the southwest corner of the state.

Due to less Mississippian rock presence in Iowa, the Mississippian aquifer is only present in approximately 60 percent of the state, where it is overlain by shaley Pennsylvanian rock, Cretaceous rocks, or glacial deposits (Olcott 1992). Like that of the Silurian-Devonian aquifer, the Mississippian aquifer is composed primarily of carbonate rock, but it can also contain sandstones and siltstones. This means the porosity and permeability, the ability for the rock to transfer water, is dependent on the secondary openings within the aquifer like the Silurian-Devonian aquifer. Therefore, the aquifer is most extensively used where it forms bedrock or where it is connected with other shallow aquifers, like the Cretaceous aquifer in northwestern Iowa. Primarily though, the aquifer is used where it is bedrock. Water from where the aquifer is connected to the Cretaceous aquifer tends to be relatively hard water with greater concentration of dissolved solids when compared to where it is bedrock. This does not make the Mississippian aquifer unused in these areas, rather just less likely to be used over the overlying Cretaceous aquifer.

The Cretaceous aquifer is located in northwestern Iowa where it is usually the only ground-water source, besides the surficial aquifer system and the small part of the Mississippian aquifer that is connected to it (Olcott 1992). This aquifer is primarily composed of sandstone, but it can be confined in places by limestone and shale beds. Otherwise it is overlain by glacial deposits. Because is it usually the only ground-water source, the Cretaceous aquifer is highly used to supply domestic, small community, and agricultural needs. The problem with the aquifer is that it contains high concentrations of dissolved solids such as calcium, magnesium, and sulfates. Of the dissolved solid concentrations, sulfate tends to be very high compared to normal. This is because gypsum deposits and other sulfate bearing rocks in the Cretaceous rock dissolve and leach in to the ground water causing an increase in sulfate concentrations. Increased dissolved solids result in very hard water, but few other sources for ground-water require those living in the area of the Cretaceous aquifer to use it anyways.

The final ground-water source in Iowa is the surficial aquifer system. Consisting primarily of glacially deposited clay, these aquifer systems have minimal permeability and are poor ground-water sources for the state. The only important aquifer systems are next to the Alluvial Plains, which contain highly permeable sediment that can supply plenty of ground water. This aquifer system is hydraulically connected to the local streams throughout the state due to its closeness to the surface, effortlessness of recharge from precipitation, and short ground-water flow systems (Olcott 1992). The amount of connection is highly dependent upon the permeability of the aquifer. Simply, the connection is a direct relationship with the permeability. The greater the permeability is, the greater the connection will be. Since the material is primarily highly permeable alluvium, connection to the streams is great. This high connectivity can lead to polluted ground water if the stream becomes polluted through agriculture runoff or inappropriate dumping into the stream. Otherwise, the aquifer system serves as an excellent ground water source throughout the state. Besides ground water sources, the surficial aquifer system also serves to allow water to flow into bedrock aquifers, recharging them.

Precambrian

The Precambrian rocks in Lee County lie deep below the surface. So deep in fact, they have never been directly observed. This is because no drill cores have been drilled in the county that surpasses 2000 feet. The deepest drill core that has a determined stratigraphy was drilled a total depth of 1850 feet in the city of Donnellson. At the bottom of this core, it was determined that the last 100 feet of the strata contained only the top two layers of Cambrian rock, which is short of the Precambrian rocks below. Even in the counties surrounding Lee County, no drill cores have been made that drill past the Cambrian strata and into the Precambrian rocks below. The reason for this is mainly based on the composition the Precambrian rocks below. Most cores are drilled because some entity is trying to tap an aquifer for water. Since the crystalline aquifer contained within the Precambrian rock is a poor quality aquifer, it serves no purpose to be drilled to unless gas or oil is expected to be found. Because there is little chance for oil or gas to be found, no drill cores will ever be drilled into Lee County’s Precambrian rock.

Using various indirect measurements, it is believed that Lee County lies in what is considered the eastern granite-rhyolite province. This province is composed mainly of, as the name states, rhyolite and granite plutons. The span of the province is not well known, but it is estimated that its spans a majority of the eastern Midwest as see in Figure 9. Unfortunately, not much is known about this province since practically all of its samples come from drill cores, of which there are few. The reason for this is because of the rare occurrence of oil and gas exploration targets and its substantial depth. Of the samples there are, radiometric dating of the zircons, a mineral containing radioactive uranium, found in the samples dates back to approximately 1.4 billion years (Catacosinos 1996).

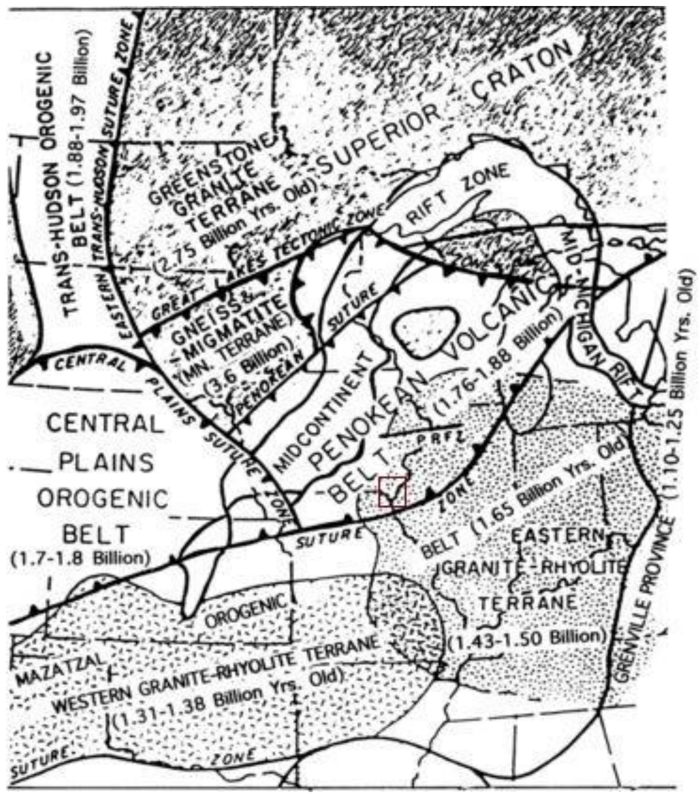

Figure 9 Precambrian terranes of the Midwest. Lee County shown in red box with underlying eastern granite-rhyolite province. Midcontinent Rift System in west-central Iowa. Adapted from Anderson 1998.

There are also mafic igneous rocks present in the province, but they are scarce and are only located near linear rift structures, and it is estimated that these rifts postdate the province (Catacosinos 1996). Also metamorphic and more intermediate igneous rocks do not appear in any of the samples. Even sedimentary rocks are restricted to specific areas of the province. This suggests that the eastern granite-rhyolite province formed in an area of purely felsic material with limited weathering. For this to happen, Lee County back in the Precambrian time must have been an area of cooling felsic lavas and magmas, free from any zones of rifting that would introduce mafic material. This is much different than most of the state of Iowa's Precambrian time. As stated in the overview of the state's geologic history, most of the state is covered in mafic igneous and metamorphic rocks because of the Midcontinent Rift System as seen in Figure 9. The reason this did not affect Lee County and cover or distort its felsic rocks is because of its proximity to the rift. Since the rift area is almost half a state away, mafic rocks and sediments were not able to drift far enough to reach Lee County. Therefore, the county was left untouched and was able to form the granites and rhyolites below.

Cambrian

Due to its age, the Cambrian like the Precambrian is buried deep below the surface in Lee County. In contrast to the Precambrian, Cambrian strata have been discovered in three drill cores across Lee County. Of the six formations contained within the Cambrian, only the Jordan and St. Lawrence have been reached. Looking at the three drill cores, one taken from the city of Donnellson and two from Keokuk, the St. Lawrence starts approximately 1797 feet down below Donnellson and slopes up to begin at 1675 feet below Keokuk. These cores stopped about 50 feet down from the top of the St. Lawrence and end before the bottom of the St. Lawrence was reached, therefore it is difficult to get an accurate thickness of this formation. Each core, though, agrees in the composition of the rock layer saying that the stratum is mainly composed of dolomite with a partial amount of sandstone. From this, it can be inferred that during the time of deposition that Lee County was most likely a shallow marine environment where carbonaceous material could accumulate to form the limestone that was transformed into the dolomite. Also the sea was shallow enough that some sand particles were able to accumulate in the limestone.

For the Jordan, the drill cores show that in Donnellson the stratum begins at 1745 feet and has a thickness of 52 feet where it lies distinguishably on top the St. Lawrence Formation. The thickness decreases for the cores in Keokuk, which start between 1635 and 1630 feet below the surface and end at 1675 feet down. This drop in thickness as you progress towards the South can be seen in Figure 10, which shows the thickness and distribution of the Jordan in Iowa. The lithology of the Jordan stratum in Lee County is primarily quartz sandstone with some dolomite found within. Again like the St. Lawrence, it is assumed that Lee County was still under a shallow sea while the Jordan accumulated. The only difference in the environment can be inferred from their lithology. Since the Jordan has more sandstone than dolomite compared to the

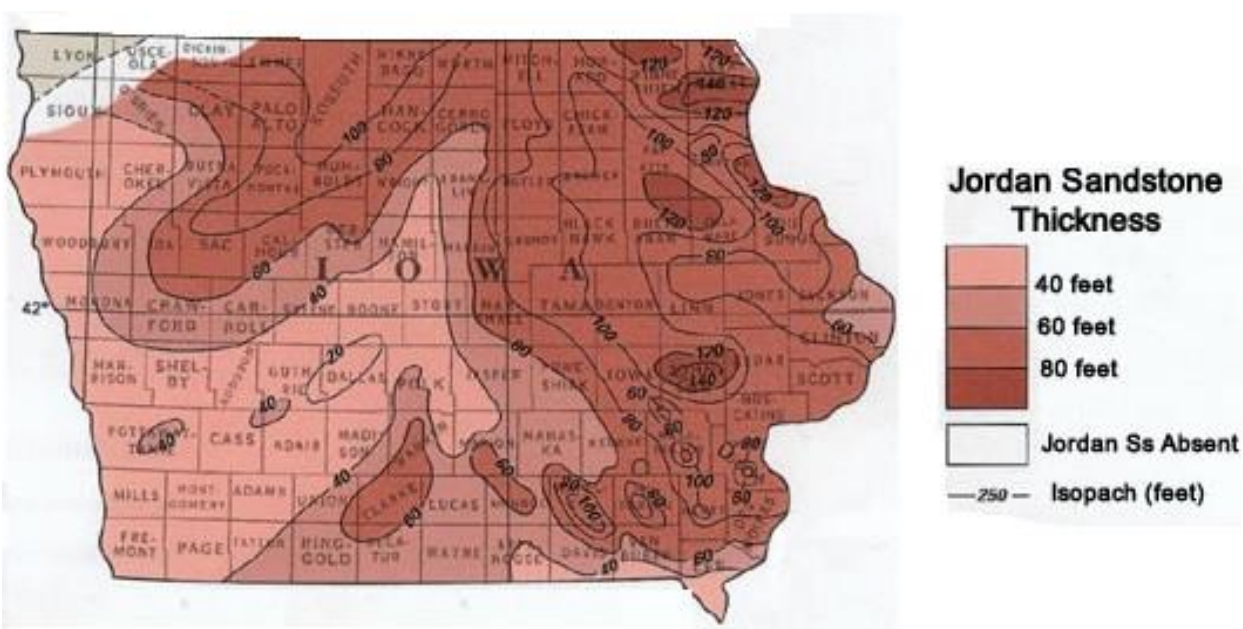

Figure 10 Thickness and distribution of Jordan sandstone in Iowa. Adapted from Olcott 1992.

St. Lawrence, it is the case the sea must have experienced a minor regression, enough to causes the sea level to drop, making it easier for sands to accumulate and somewhat harder for carbonates to form.

The purpose for drilling into these strata was to tap into the Jordan aquifer, which is a part of the St. Peter-Prairie du Chien-Jordan Aquifer in the Cambrian-Ordovician aquifer system. Even though these cores do not stop within the Jordan, but rather the St. Lawrence, it is still the case they are pumping water from the Jordan aquifer. This is because most Jordan aquifer wells are designed to drill 25 to 50 feet into the St. Lawrence dolomite and to be cased and grouted from the surface to exclude all overlying aquifers (Horick 1978). The three wells that use this aquifer in Lee County are large capacity, artesian wells, one of which supplies municipal water to the city of Donnellson. In large urban areas like Cedar Rapids or Des Moines, the aquifer is known to be overdrawn, but due to the relatively small size of Donnellson the recharge rate of the aquifer is more than adequate to compensate for the water drawn. Historically in the 1970s, Donnellson pumped around 40 million gallons of water per year from the Jordan aquifer (Horick 1978). This number has stayed relatively stable in recent years even though the population of the city has increased by approximately 100 people. The water quality is rated good to fair containing somewhere between 500 and 1500 mg/L of dissolved solids in Lee County (Horick 1978). Even though the water is rated fair at least, the water is usually treated to remove excess iron found within it.

As for the other four strata that are not visible in the drill cores, it would be the case that if a well was drilled deeper the remaining strata would be there. Since there are no cores containing them, the thickness and composition of them can only be hypothesized based upon the samples from nearby counties that do have samples. Using this idea, it is believed that the Lone Rock, Wonewoc, Eau Claire, and Mt. Simon strata would be much thicker than the Jordan stratum in Lee County. It is also assumed that their composition would be like that of the Jordan, made of quartz sandstone mixed with a little dolomite, but proof of this is impossible without deep cores.

Ordovician

Of the five Ordovician formations in Iowa, only the oldest four are found in Lee County as seen in the stratigraphic column shown as Figure 11. All four of these are found in several cores throughout the county. The Prairie du Chien, the oldest of the formations, lies directly on top of the Jordan Formation from the Cambrian. This formation begins around 1745 feet below in the northern part of the county, while in the southern part it begins around 1635 feet down. Varying in thickness, the Prairie du Chien has an average thickness around 600 feet. The composition is consistent throughout, primarily that of dolomite with slight parts chert and sandstone. This stratum composition suggests that Lee County was in a carbonate shelf

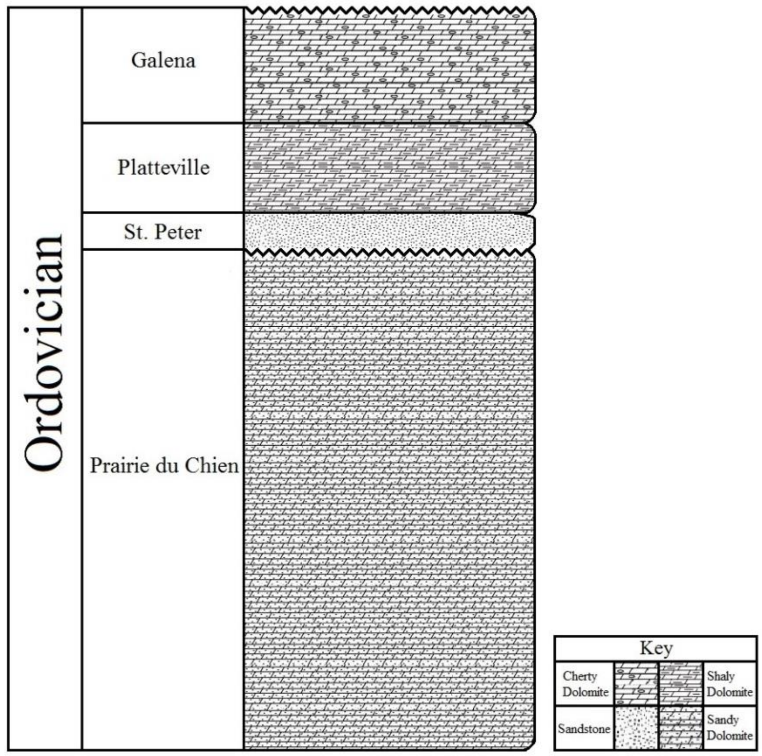

Figure 11 Stratigraphic column of Ordovician of Lee County.

environment with some sandy shoreline present nearby. The chert appearance can be caused by various factors, but indicates a definite shallow sea environment. One factor for chert's appearance is a biological origin, which results from silica tests accumulating in the sea floor. The other reason could be from direct precipitation from silica rich fluids that fill voids in the rocks around it.

After the time of sea regression and erosion, the St. Peter Formation was deposited unconformably on top of the Prairie du Chien. The thickness of the St. Peter Formation varies from 30 to 60 feet and has a deepest depth at 1161 feet in the northern part of the county and 990 feet in the southern part. The composition of the formation is purely quartz sandstone, which highly advocates a potentially beautiful sandy beach or nearshore environment for Lee County during this time. Here the quartz grains could be well washed and sorted to provide the super mature sandstone that the St. Peter Formation is made of.

These two formations along with the previously mentioned Jordan Formation lie within the St. Peter-Prairie du Chien-Jordan Aquifer in the Cambrian-Ordovician aquifer system. Of these two formations, four wells in Lee County lie within the formations, three in the Prairie du Chien and one in the St. Peter. These four wells share the same properties as the other three that are within the Jordan Formation, since they are all hydraulically connected. Three of these wells are found in Keokuk, while the other is near the township of Argyle.

The Platteville Formation environment in Lee County makes a transformation from the St. Peter's nearshore sandy beach environment to a carbonate and muddy marine shelf. This can easily be seen in many local cores which all have the same primary lithology of dolomite and a secondary lithology of dense shale. The formation lies, like all other strata, deeper in the north of the county and shallower in the south. In the north, the stratum lies approximately 1130 to 1150 feet down, while in the southern part it has a depth of 950 to 935 feet. The total thickness is a consistent 110 feet throughout the county.

The final visible formation, or more accurately group, that is located in Lee County is the Galena Group, which is composed of dolomite and chert and formed in the same conditions as the Prairie du Chien Formation. The Galena Group is well known in northern Iowa and southern Wisconsin as a source for minable sulfide minerals. Mining for sulfide minerals, though, is not performed in Lee County. Only the Decorah and Dunleith formations of the Galena Group are found in Lee County. Taken together, they have a widely varying thickness depending on the opinion of the core sample, but a relatively common value is approximately 140 feet. This group rests directly above the Platteville formation, so the base of it is about 1120 feet deep in the northern part of the county and 840 to 820 in the southern part.

The problem with this layer is its upper limit. A massive unconformity lies between it and the next identified stratum in the Devonian, because of this most cores have a 50 to 100 foot unidentified region between the known Galena group and the Devonian stratum above. After analyzing this region in the cores, it can be seen that they all have the same composition of dolomite and chert. This is a similar composition as the other formations in the Galena Group. Since the overlying and missing strata that would be above the unidentified formation are expected to not have this composition, it is most likely the case that this is still part of the Galena Group, but no definite formation could have been assigned.

Even though the Galena Group is within the Cambrian-Ordovician aquifer system, it is not a part of one of the large aquifers found within the system, such as the prominent St. Peter-Prairie du Chien-Jordan Aquifer. Instead it is a small aquifer known as the Galena aquifer. Several wells in Lee County tap into the Galena aquifer for water. The aquifer is considered a minor aquifer (Figure 12). The difference between that and a major aquifer is the yield of water. The Galena Group only yields a small amount of water, due to its composition of dolomite which has a relatively low porosity when compared to the St. Peter-Prairie du Chien-Jordan Aquifer's sandstone's porosity. In Lee County, this low yield can be seen through the use of the wells tapping into the Galena Group. All wells are restricted to private or personal use, which usually have minuscule pumping rates compared to municipal wells.

Age	Rock Unit	Description	Thickness Range	Hydrogeologic Unit	Water-Bearing Characteristics
Quaternary	Alluvium	Sand, gravel, silt and clay	0 - 350 (feet)	Surficial aquifer	Fair to large yield (25 to 100 gpm)
	Glacial Drift (undifferentiated)	Predominantly till containing scattered irregular bodies of sand and gravel			Low yields (less than 10 gpm)
	Buried channel deposits	Sand, gravel, silt and clay			Small to large yields
Pennsylvanian	Des Moines Series	Shale, sandstones, and limestones; mostly thin	0 - 75	Aquiclude	Does not yield water
Mississippian	Meramec Series	Sandy limestone	0 - 400	Mississippian aquifer	Fair to low yields
	Osage Series	Limestone and dolostone cherty; shale			
	Kinderhook Series	Limestone, oolitic and dolostone, sherty; also siltstone			
Devonian	Maple Mill Shale Sheffield Formation Lime Creek Formation	Mostly shale, with siltstone in the upper part and limestone in the lower part	200 - 300	Devonian aquiclude	Does not yield water
	Cedar Valley Limestone Wapsipinicon Formation	Limestone and dolostone contains evaporites (gypsum), in southern half of Iowa	100 - 175	Devonian aquifer	Fair to low yields
Ordovician	Galena Formation	Dolostone and chert	900 - 1050	Minor aquifer	Low yields
	Decorah Formation-Platteville Formation	Limestone, dolostone and thin shale, includes sandstone in SE Iowa		Aquiclude	Does not yield water
	St. Peter Sandstone	Sandstone		Cambrian-Ordovician aquifer	Fair yields
	Prairie du Chien Formation	Dolostone; sandy and cherty			High yields (over 500 gpm)
Cambrian	Jordan Sandstone	Sandstone	40 - 60		
	St. Lawrence Formation	Dolostone		Aquitard	Does not yield water
	Franconia Sandstone	Sandstone and shale			
	Dresbach Group	Sandstone		Dresbach aquifer	High to low yields *
Precambrian	Undifferentiated	Coarse sandstones; crystalline rocks		Base of groundwater reservoir	Not known to yield water

* highly mineralized in Lee County

Figure 12 Description of aquifers of Lee County. From Gordon 1980.

Silurian

While Silurian rock forms some of the most resilient rock in Iowa, it is a time not recorded in Lee County's geology. The Silurian strata were only deposited in a band that runs from eastern Iowa down to the southwest as seen in Figure 13. In places not covered by this band like Lee County, it is thought that some deposition may occurred, but a large period of exposure at the end of the period completely removed it and the underlying Maquoketa as stated above. This makes determining the environment of Lee County during the Silurian very difficult. In the locations in Iowa where Silurian rocks were deposited, the environment would have been marine shelves with varying amounts of water salinity throughout the period, creating mainly carbonate rocks. So it is assumed that Lee County would have had a similar environment, but either the deposition was less or the erosion at the end of the period was more intense causing the absence of the strata in the county's rock record.

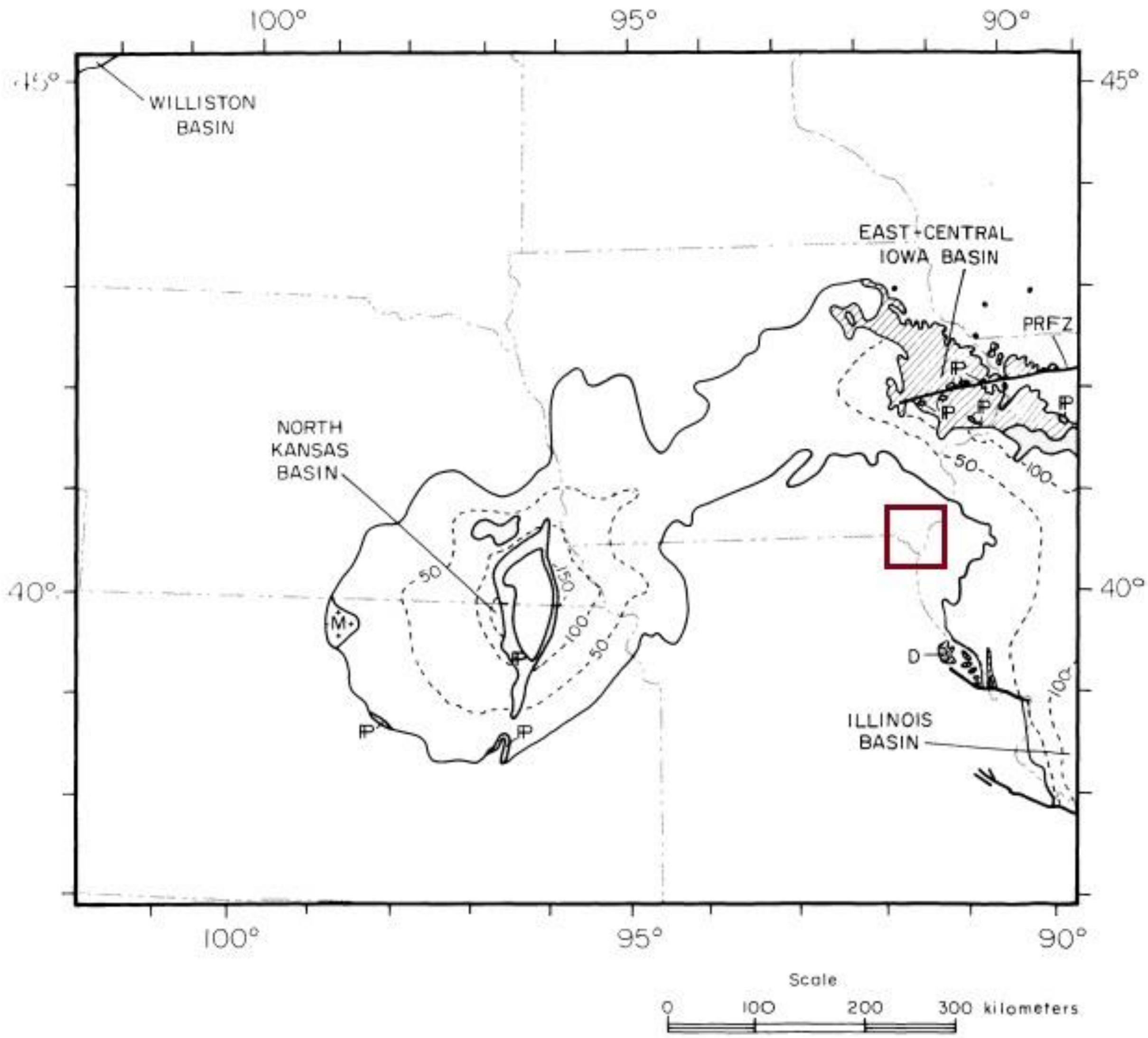

Figure 13 Distribution and thickness of the Silurian in Iowa. Lee County boxed in red. Adapted from Ludvigson 1988.

Devonian

Of the twelve Devonian formations in Iowa, only five are found within drill cores from the county. These five formations are not consecutive in Iowa's overall stratigraphic column. Instead, they are relatively spread out. First of the formations is the Pinicon Ridge Formation that mostly lies on top of the unidentified stratum with the rest lying above the Galena Group from the Ordovician. This helps potentially confirm that the unidentified stratum is most likely from the Galena Group of the Ordovician. The Pinicon Ridge Formation has a varying depth throughout the county. The deepest part is near West Point in the northern part of the county sitting around 820 feet down and shallowest is near Keokuk a depth of 545 feet. The average depth is approximately 700 feet. Thickness of the layer averages to 37 feet with deviation of only

10 feet. Pinicon Ridge's composition is mainly limestone with some thin layers shale. This indicates a marine environment of restricted water circulation so that shales could form along with carbonate deposits.

The next formation present in Lee County is the Little Cedar Formation, which rest directly above the Pinicon Ridge Formation. Only identified in about half of the drill cores that reach its depth, these cores are still spread out enough throughout the county to assume that the formation is most likely located throughout, but just not identified. Those that do not have it have a layer of unidentified stratum in its place of similar composition to that of the Little Cedar. Noticing that the layer above the Little Cedar has a drastically different composition, it seems to indicate that this unidentified layer most likely belongs to the Little Cedar. Depth of the layer averages to 620 feet with variations deviating up to 100 feet, while the thickness is a relatively constant 95 feet. Having a similar composition and environment of deposition to Pinicon Ridge, the composition is mostly that of limestone with a lesser addition of shale which again indicates a calm shallow marine environment.

Only the Pinicon Ridge and Little Cedar formations make up the Silurian-Devonian aquifer in Lee County. Due to the absence of the Silurian rock and large presence of shale in the overlying "Yellow Spring" Group, these two formations are the only two water bearing formations that make up the aquifer. Since the thickness of this aquifer is relatively small in Lee County, water yield from it is low. This is noticeable from the minimal use of the aquifer. Only a few wells tap into it, and all of them that do are privately owned and are used for agricultural purposes. Also water quality of the aquifer is low throughout the county. Concentration of total dissolved solids is somewhere between 2,500 to 10,000 mg/L, which way exceeds the recommended maximum value of 1,000 mg/L (Gordon 1980). Therefore, use of the Silurian-Devonian aquifer is minimal within Lee County.

Lee County stratigraphy does not contain any rocks from the "Upper" Cedar Valley Group, but instead jumps to the Lime Creek Formation in the "Yellow Spring" Group. The only two explanations for these missing strata are that either the rocks were not deposited or an erosional period caused an unconformity. Due to other unconformities associated with these strata across the state, this is the most likely explanation. Therefore, this means that the seas covering Lee County during the Devonian must have regressed during the end of the Upper Cedar Valley Group's depositional period to expose any deposited rock and erode it away.

As for the Lime Creek Formation, it is clear that the formation is present throughout the entire county, because of its presence in every drill core that is deep enough to reach it. On average, Lime Creek has a depth of 585 feet. The thickness of Lime Creek is highly variable from 10 to 150 feet. This discrepancy seems to correlate with the cores missing the Little Cedar Formation. Those that do not have it, instead have these assumed thicker Lime Creek layers. The problem is that the composition of these layers is so different, one being limestone the other shale, that confusing them and adding one to the other is not likely. Instead this suggests that the

Lime Creek Formation had an uneven deposition, allowing for more shale to be deposited in some locations rather than others. This variation suggests an environment of calm, shallow waters on a shelf margin with uneven topography to allow for this thickness variation.

On top of the Lime Creek Formation in Lee County lies the Sheffield Formation. The deepest part of the formation is near West Point with a depth of 580 feet. Having a depth of almost half that, the shallowest part of the formation is found in the northeast corner of the county near Fort Madison with a depth of only 260 feet. Having a constant thickness and composition, the Sheffield Formation averages about 130 feet of shale throughout the county only deviating about 15 feet. For a depositional environment, this thick layer of shale suggests a shallow marine shelf that must have had low oxygen levels to inhibit carbonate from forming. Calm waters must have been present for a long period so that fine particles could filter out of the water and form this shale layer.

The final formation found in Lee County is the Maple Mill Formation. Maple Mill normally over lays the Aplington Formation in most of Iowa, but as Figure 14 shows the Aplington Formation does not span into Lee County. This is due to no deposition occurring during this period in these locations, but just because there is no visible deposit does not mean that none occurred. Instead, it may just be that it is shaley facies that cannot be distinguished from the underlying Sheffield Formation (Dorheim 1969).

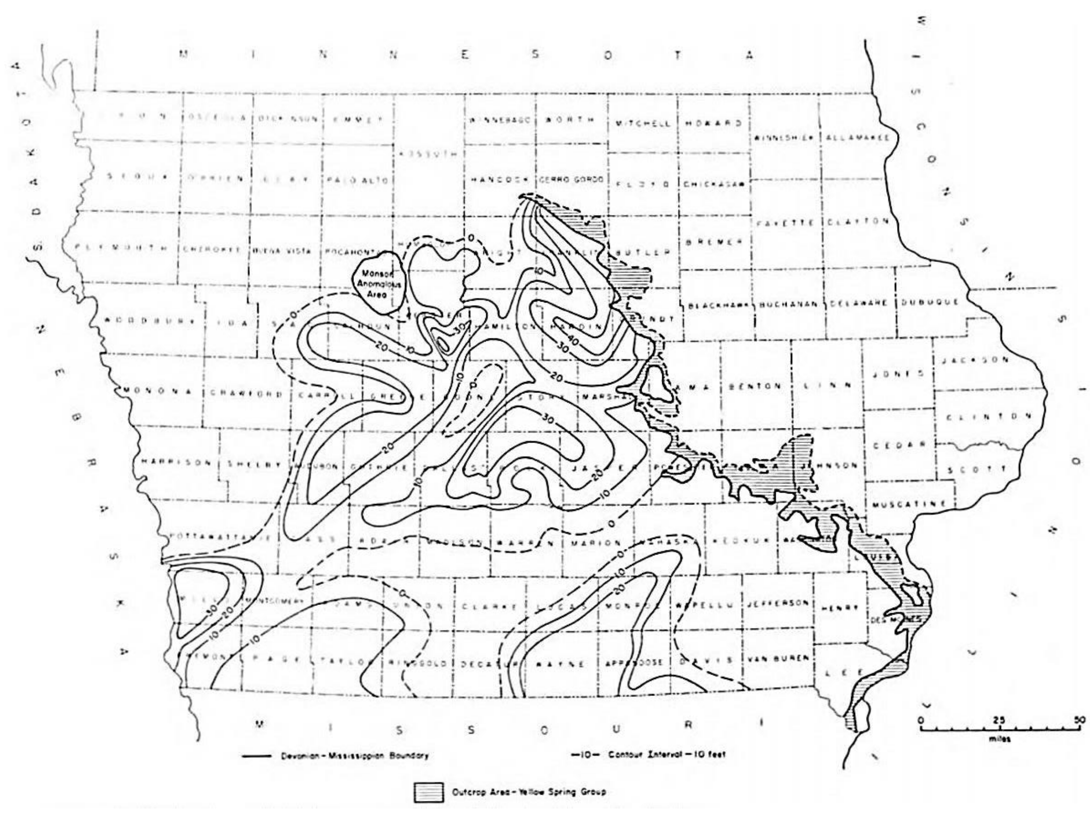

Figure 14 Distribution and thickness of the Aplington Formation in Iowa. From Dorheim 1969.

The Maple Mill Formation is the only Devonian stratum that makes up part of Lee County's bedrock. Technically, the Maple Mill Formation here is composed of the actual Maple Mill Formation and the English River Formation. The English River Formation is relatively thin and its contact with Maple Mill is gradational, making it challenging to recognize in subsurface studies, therefore the English River is usually included with the Maple Mill Formation (Dorheim 1969). The bedrock is located in a thin band that runs from the northeast corner parallel to the Mississippi River down to the southern tip as seen in Figure 15. Depth of the rock grows as distance increases from the center of the band. Close to the center, depth averages to 250 feet, while far away from the bedrock portion of the stratum depth can reach up to 467 feet. Thickness of the formation averages to 106 feet with quite a bit of deviation. This deviation can be as much as 100 feet, which is unusual for the thickness of a layer. The formation is primarily composed of shale with the English River part, having a siltstone composition. Just like the Lime Creek and Sheffield Formations, Maple Mill's depositional environment is that of a shallow marine shelf with low oxygen levels.

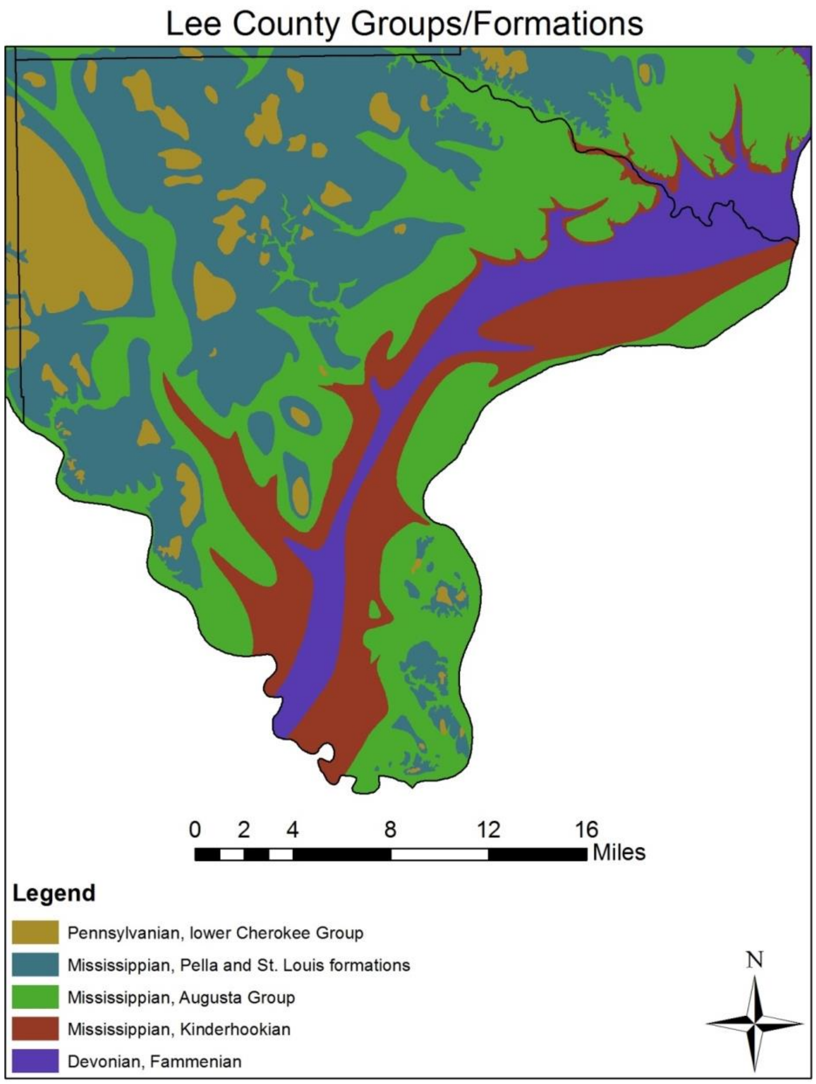

Figure 15 Distribution of bedrock in Lee County.

Mississippian

Mississippian rock is the most prevalent bedrock in Lee County (Figure 15). All formations can be found in Lee County's drill cores, and many can be found exposed at the surface (Figure 16). The only series not clearly exposed at the surface is the Kinderhookian Series, but its formations are well known from drill cores. The McCraney Formation is found in most drill cores that are deep enough to reach it. The only ones that do not contain it are those that were drilled within the thin Devonian bedrock belt. Depth of the McCraney Formation increases as distance from the bedrock portion of the stratum increases. At the bedrock portion near Fort Madison, depth averages to 275 feet, while far away depth averages to 405 feet. Thickness of the formation varies from 10 to 75 feet with the thinnest part being found where the formation is bedrock. Composition throughout the county is that of a limestone and dolomite blend with some locations having chert found within it. From this composition, a depositional environment of a shallow restricted marine sea that was transgressing over the county and state can be inferred.

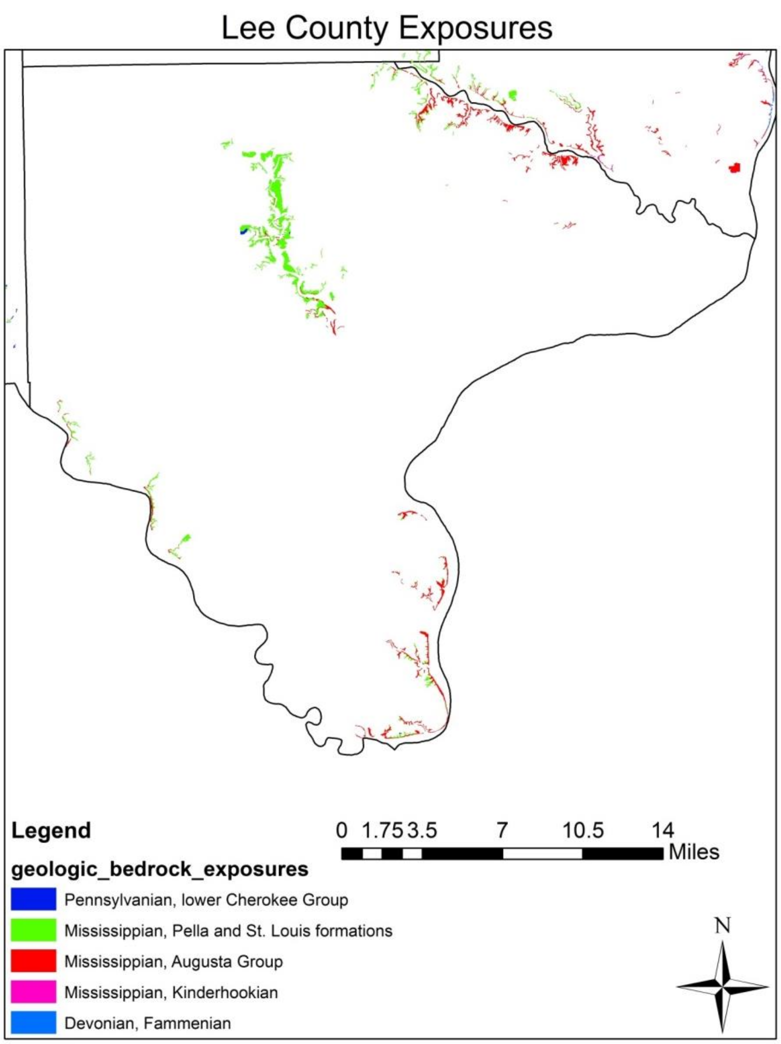

Figure 16 Distribution of bedrock exposures in Lee County.

The next formation above the McCraney is the Prospect Hill Formation. This formation, like the McCraney, is only known from drill cores that lie outside the Devonian bedrock belt. All but two drill cores outside this belt contain the Prospect Hill Formation. The two that do not have it, are ones where the McCraney Formation is bedrock. Most Prospect Hill bedrock is also located near Fort Madison, like that of the McCraney. So depth of the formation increases as distance from this area increases. Depth averages 300 feet, but extreme highs and lows are from 415 to 150 feet. Thickness again varies depending on if the formation is bedrock or not. Where the formation is bedrock, the thickness is around 10 feet. While covered by other formations, the thickness can reach almost 80 feet. Drill cores tell the composition of the formation to be primarily quartz siltstone interbedded with shale. This composition suggests a standard marine environment with the quartz siltstone indicating an influx of eroded land based sediments during the time of deposition.

The Starrs Cave Formation is not quite as prominent as the Prospect Hill and McCraney Formations in Lee County. Only found in approximately three-fourths of the drill cores that should contain it, Starrs Cave is most likely an exceedingly small part of Lee County's bedrock as inferred from drill cores due to its thickness. Starrs Cave is especially thin with an average thickness of just over 10 feet and a maximum thickness never over 20 feet. Being completely composed of oolitic and fossiliferous limestone allowed for it to be quickly weathered away when exposed, and thereby preventing it from appearing as bedrock. An environment of deposition for the formation is most like that of a very shallow marine setting with moderate wave action that could agitate the sea floor and form ooids.

Even less prominent than the Starrs Cave Formation is the Wassonville Formation due to potential erosion that caused a disconformity between it and parts of the overlying Burlington Formation. Thickness of the layer is even less than that of Starrs Cave, averaging only 8 feet thick. Depth of the stratum varies from 350 feet to a shallow 135 feet. Averages of the depth, though, show that the formation is more common around a depth of 300 feet than that of shallow depths. Composed of dolomite and limestone with some instances of chert, a depositional environment must have been a shallow marine setting that was a bit deeper than that of the Stars Cave Formation.

The Osagean Series contains the most prevalent part of the Mississippian in Lee County. The oldest and most widespread of the group is the Burlington Formation with its three members, Dolbee Creek, Haight Creek, and Cedar Fork. Looking at the formation, it has an average depth of 235 feet throughout the county, but variation occurs with 150 foot depths near Keokuk and 350 foot depths near the western edge of the county. Where the formation is not bedrock, the thickness is extremely consistent deviating slightly from its 70 foot average. Composition varies between each member. The Dolbee Creek Member is primarily limestone with only a little bit of dolomite. Haight Creek is different with its intense concentration of chert composing its primary lithology and a secondary lithology of limestone. Cedar Fork goes back to a main component of limestone, but still has some chert found within. These variations demonstrate the two transgressive-regressive cycles that occurred while the Burlington Formation was deposited, where water level fluctuated from shelf depths to shallow wave base depths. Many outcrops of this formation can be seen in the northeastern part of the county shown by Figure 16. More specifically, a few isolated exposures can be found in the bed and banks of Lost Creek southeast of the township of Denmark; in the bed and banks of the Skunk River, and in minor quarry openings to the west of Wever (Van Tuyl 1922).

Above the Burlington lies the Keokuk Formation whose outcrops in the county can easily be seen in the city of Keokuk along the Mississippi River bluffs. Similar to the Burlington Formation, the Keokuk Formation has a primary composition of limestone with chert and dolomite. The environment of the formation is assumed to be that of a middle-shelf setting. Also due to concentration of chert in the lower part of the formation, it is assumed maybe a large influx of siliciclastic clay from the nearby land could have caused this chert to form (Anderson 1998). Thickness of the Keokuk Formation is a relatively stable average of 70 feet, but slightly more deviation occurs from this value when compared to the Burlington Formation. Depth is inconsistent due to outcrops appearing along the Mississippi River. Depth can be less than 100 feet when near the river, or up to 250 feet when along the county's western edge.

The final prominent formation of the Osagean Series in Lee County is the Warsaw Formation. Having an average depth of 130 feet and a maximum of less than 200 feet, the formation is found in almost all drill cores in the county due this shallow depth. Also because of this depth and mass amount of cores containing the formation, its composition can be seen precisely as a combination of shale and dolomite. This supports a local depositional environment of a marine shelf, deep enough to prevent wave action from stirring up the settling clays. Thickness varies greatly between 20 and 80 feet even where the formation is not bedrock. This is due to an unconformity that occurred as the seas regressed and exposed the Warsaw Formation to weathering. Some cores do not even contain the Warsaw due to the extensive weathering that occurred.

After this period of weathering, the Salem Formation was deposited unconformably on top of the Warsaw Formation. This formation is only found in extreme southeast Iowa, thereby making Lee County one of the few counties in the state to contain it. Even though it can be found in Lee County, it is still not very common, appearing in less than half of the drill cores that could contain it. Depth of the stratum averages around 115 feet, with a few outliers that have shallow depths around 50 feet. The thickness is relatively constant, staying within 10 feet of the 30 foot average. Inconsistencies are found in the composition of the formation. All agree on a primary composition of dolomite, but secondary lithology varies between sandstone, limestone, chert, and shale. This seems to indicate that the marine setting in Lee County must have undergone a transgressive-regressive cycle during the time of deposition to give all of these different secondary lithologies.

The St. Louis Formation in Lee County rests on top of either the Salem Formation or the Warsaw Formation. Depth of this formation is relatively shallow due to it being a large part of the bedrock in Lee County. The range of depth is from 5 to 165 feet with an average of 85 feet. Thickness of the stratum is also largely variant. Having an average of 45 feet, the thickness of the formation spans anywhere from 4 to 90 feet independent of location. Composition of the St. Louis Formation is primarily limestone with varying secondary lithology, which usually consists of sandstone, but can also be dolomite or chert. Like the Salem Formation, this variation in lithology supports the thought that the formation records several transgressive-regressive cycles that occurred while it was deposited.

The final formation in the Mississippian is the Pella Formation, which lies unconformably on the St. Louis Formation. This formation is not very common in Lee County, and it is only found in two drill cores near Donnellson. These cores have the depth of the layer at 70 and 60 feet with a thickness of 7 and 15 feet respectively. Composition of the two cores is exactly the same, shaley limestone with some interbedded chert. This composition represents an influx of land based muds associated with a regressing sea environment. The sea eventually completely regressed and exposed the Pella Formation causing little of it to be left, and the regression caused an unconformity to form between the last of the Mississippian rock and the upcoming Pennsylvanian rock.

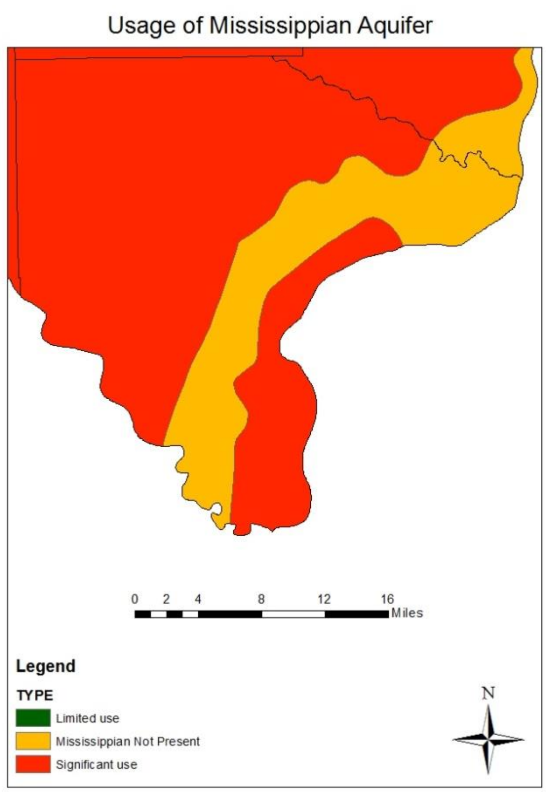

Figure 17 Usage of the Mississippian Aquifer in Lee County.

All of these Mississippian formations are a part of the Mississippian aquifer. This aquifer is the most widely used aquifer within Lee County with significant use everywhere in the county except where Mississippian rock is not found (Figure 17). The aquifer is a relatively thick 300 feet in the northwestern edge of the county, and decreasing in thickness towards the southeast (Figure 18). Most private wells using it rely on the Mississippian aquifer due to its high quality water with most wells having water with less than 1,000 mg/L of dissolved solids. Only those located at the western edge of the county have dissolved solid counts over 1,000 mg/L (Gordon 1980). The only problem with the aquifer is that it has low water yields and cannot be used municipally. Throughout the county where the aquifer is present, wells yield less than 20 gallons per minute, making the aquifer only effective for private use. The reason for this low yield goes back to the aquifers composition. Limestone and dolomite do not have large primary porosity, and instead rely on secondary porosity of joints and fractures to allow for water transport. Therefore, water yields of aquifers with these compositions tend to be low.

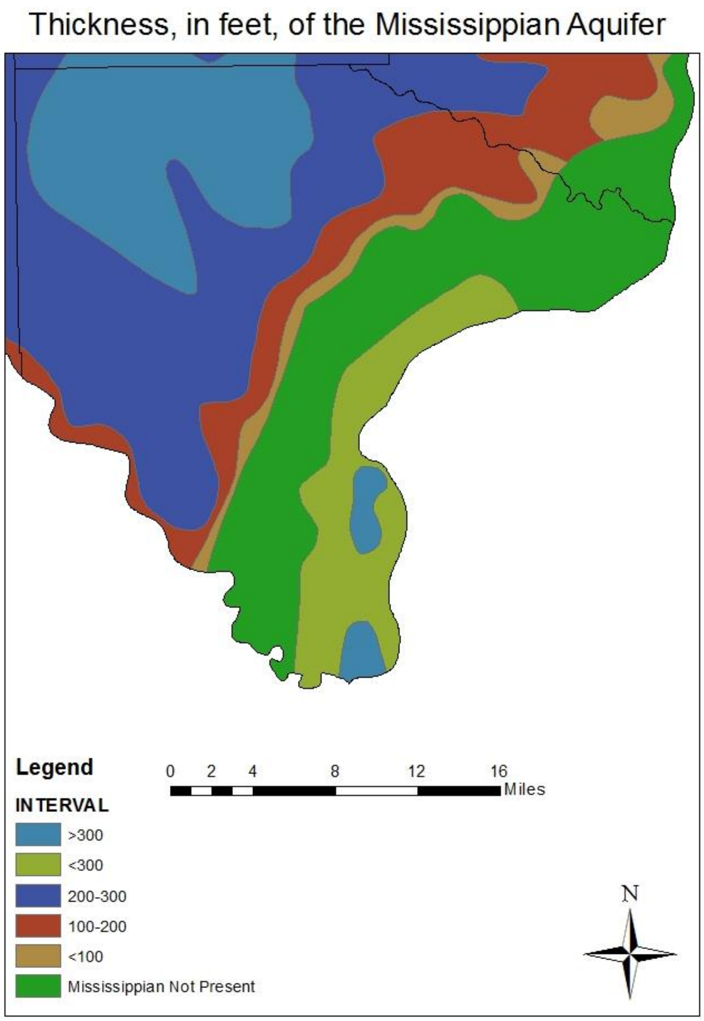

Figure 18 Thickness of the Mississippian Aquifer in Lee County.

One important thing in the Mississippian rocks of Lee is the presence of Iowa's state rock, the geode. The area around Keokuk is one of the most famous geode locations in the world, therefore it seems appropriate to briefly discuss them. Most geodes in Lee County appear in both the Keokuk and Warsaw Formations (Figure 19). Geodes are spherical like bodies of mineral matter whose outside looks like cauliflower and whose insides have been hollowed out and lined with crystals (Figure 20). This crystal lining can either completely fill the hollowed out interior or partially fill it leaving a still hollow center. Geodes with a hollow center tend to be more valuable than those that are completely filled. The type of crystal can vary from twenty different minerals, but the most common is quartz.

Figure 19 Picture of Keokuk Formation at Mississippi River bluff at Keokuk. Holes in the formation are open geodes where half of the geodes have been broken off of bluff face. Photo by author.

Figure 20 Geodes found with Lee County. Larger two approximately six inches in diameter. Photo by author.

To form a geode, many steps must be taken. Back in 1964, John B. Hayes proposed a potential formation process for the standard geode. First, the calcite concretion is formed from fine-grained carbonate sediments most likely below the water-sediment interface on the seafloor. This concretion has been thought to form around masses of decaying organic matter. Next, a coating of finely crystalline quartz replaced the calcite on the outer edge of the concretion. Then the core of the object is dissolved producing the hollow center. Finally, mineral-bearing waters filled in the hollow center and allowed for crystals to precipitate on the outer margin of the cavity. These crystals can then continue to grow toward the center of the geode. So if the crystal precipitates until the cavity is full then a solid geode will form, otherwise the geode will be left partially hollow.

Pennsylvanian

The Pennsylvanian of Lee County is exceedingly limited, only found in the western edge of the county and in small patches spread throughout. Only one group makes up all of the Pennsylvanian in Lee County, that being the Lower Cherokee Group. The location of this group can be seen in Figure 15. Since the Lower Cherokee group is bedrock, the depths that it can be found in drill cores are relatively shallow, if the rock is not exposed. Having a rather consistent depth at all locations, the Lower Cherokee Group has an average depth of 75 feet. Thickness of the layer varies throughout, with the thin parts near the edges where the Pennsylvanian meets the Mississippian and the thick parts surrounded by Pennsylvanian rock. These thin areas have only 5 to 10 feet of the Lower Cherokee Group, while the thicker parts can have up to 60 feet. Composition of the Lower Cherokee Group in Lee County is predominately shale with some secondary lithology of sandstone and limestone. This lithology suggests an environment in which shifted from coastal marine to a shallow marine shelf with low oxygen levels and calm waters that allow for the settling of fine particles to form the shale. To view these outcrops, the easiest travel is to the western border of Lee County near Farmington, Iowa, where Mississippian rock transitions into the Cherokee Group of the Pennsylvanian (Figure 16).

The reason for the limited Pennsylvanian rock can be understood from Lee County's geographical location. Most of the Midwest's Pennsylvanian outcrops, known as the Forest City Basin and Illinois Basin, are located on the outer west and east side of Lee County respectively. This is believed to be because of a poorly defined upwelling feature that is known as the Mississippi River Arch (Figure 21). The feature lies on the Illinois side of Mississippi River right next to Lee County and is considered to be Middle Pennsylvanian (Anderson 1998). Upwelling from the arch caused most of Lee County to rise up to a height that exposed the rock, preventing more deposition and promoting weathering.

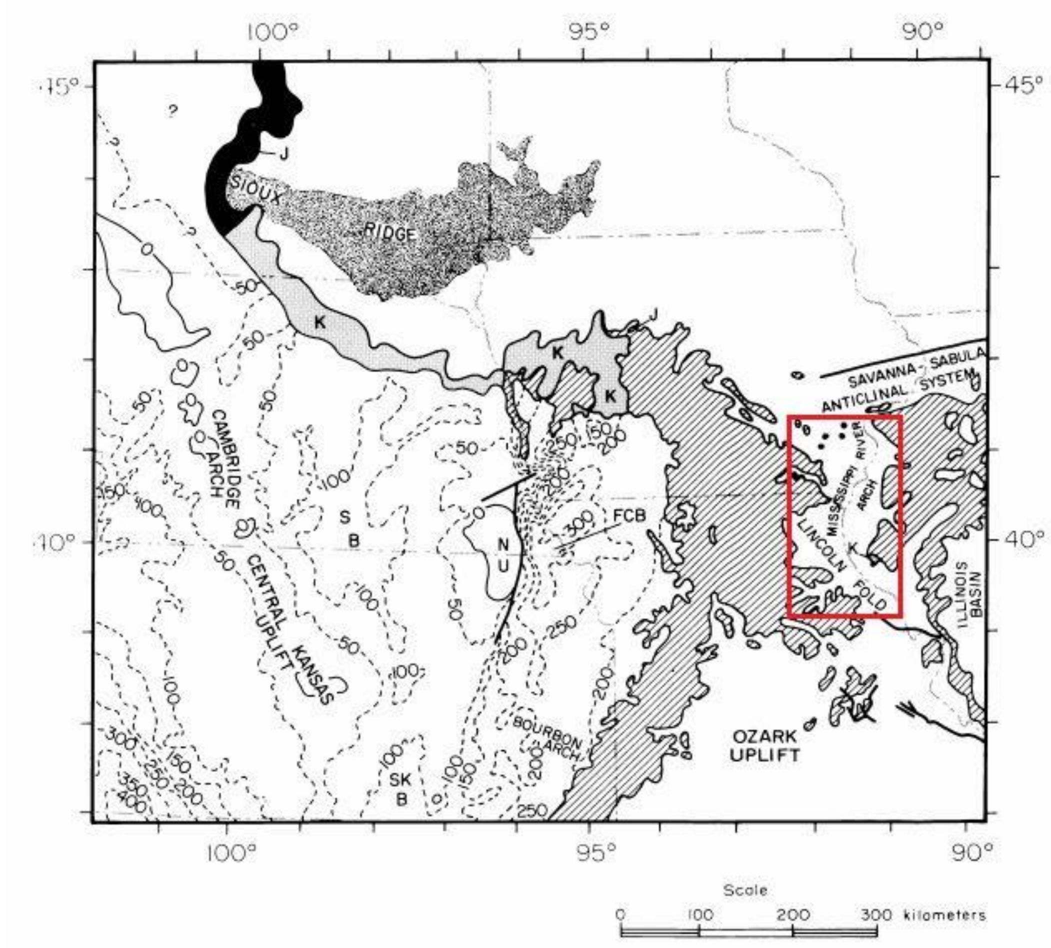

Figure 21 Separation of Pennsylvanian basins by Mississippi River Arch boxed in red. Adapted from Ludvigson 1988.

The Pennsylvanian of Lee County contains a small amount of coal, much like the rest of the state. This small amount of coal was mainly stripped, but some shafts and drift mining occurred (Keyes 1893). This occurred throughout the county starting around the 1850s, which was noted by a surveyor of the Des Moines valley in 1856 (Lees 1908). A total of 15 mines existed in Lee County, all of which harvested the Blackoak coal. This layer of coal varied in thickness from ten to fourteen inches up to three and a half feet (Lee 1908). This Blackoak coal is found within the Kalo Formation of the Lower Cherokee Group. A map of the locations of these mines can be seen in Figure 22. Only five of these fifteen mines were given official names. The most prominent of these was the Hardwick mine. This mine was once a main source for coal at the local markets within the county, but it officially closed in 1894 (Lee 1908). The rest of the mines if not already closed stopped mining by the late 1890s, ending Lee County's coal production.

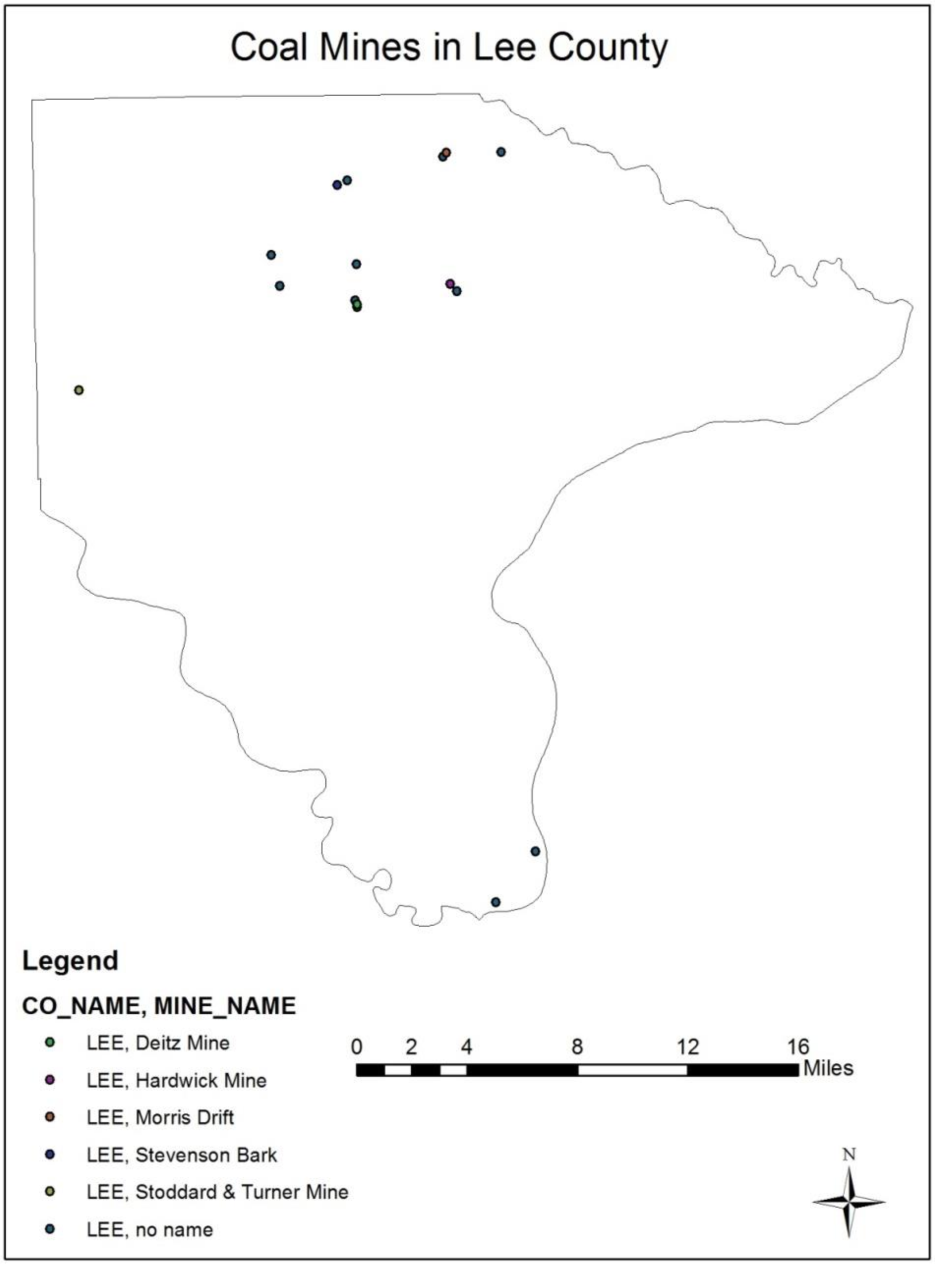

Figure 22 Locations of coal mines found within Lee County.

Cenozoic

The Cenozoic of Lee County is contained with all of its drill cores. No rocks from the Tertiary period are found in the county, only Quaternary deposits. The breakdown of these Quaternary deposits is oddly labeled as Pleistocene and Quaternary. This could be slightly confusing since technically the Pleistocene is one of two parts of the Quaternary Period, the other being the Holocene. In these drill cores though, most have a layer called the Pleistocene below the top most Quaternary layer. This seems to indicate that the Pleistocene refers to the tills deposited during the Pleistocene epoch, while the Quaternary layer most likely refers to the most recent epoch known as the Holocene.

The depth and thickness of these layers vary drastically over the county, which is due to the height of the underlying bedrock and the amount of glacial deposit accumulated. The Pleistocene layer has a range of depth from 0, or exposed to the surface, to 105 feet with an average value of 14 feet. Thickness can also vary from 320 to 5 feet, but the average of the thicknesses is around 90 feet. Composition of the Pleistocene layers are mainly that of glacial till with a secondary lithology of gumbotil, which is a sticky clay formed by weathering of glacial drift now referred to as paleosol. The Quaternary layer is always the uppermost layer in Lee County's stratigraphic columns. This means it has no starting depth due to it being on the surface. Thickness of the layer, though, has a wide range of values from 115 to only 5 feet, but in most drill cores these layers average to 37 feet. The composition of the Quaternary layers varies with depth. Most cores agree on a layer of loess that takes up most of the thickness of the measured layer. On top of this loess is a thin amount of soil or fill which is most likely of human origin and has a thickness of less than 5 feet.

The origin of this loess is hard to determine since it is windblown sediment, but it is believe to be a part of the Peoria Loess. Determining an origin for the till from the Pleistocene is also very difficult to do, but determining how it got in Lee County is possible. Most of this till came into the county from the Pre-Illinioan Glacial Stage, while some till near the Mississippi River may have also originated from the Illinioan Glacial Stage (Figure 23). These glaciers originated and were dispersed from three main centers, one at the Labrador Peninsula, a second just west of Hudson Bay in the area of Keewatin, and the last in the western Canadian mountains as seen in Figure 24 (Lee 1916). The Pre-Illinoian glaciers originated from the Labrador and Keewatin centers, while the Illinoian glaciers only originated from the Labrador center. This is why the Illinoian glaciers only reach the very eastern edge of Iowa, while the Pre-Illinoian cover all of Iowa. Therefore, any Pre-Illinoian till is most likely to have originated from the North such as Canada, Minnesota, or Wisconsin; while Illinoian till mostly originated from Illinois or Michigan.

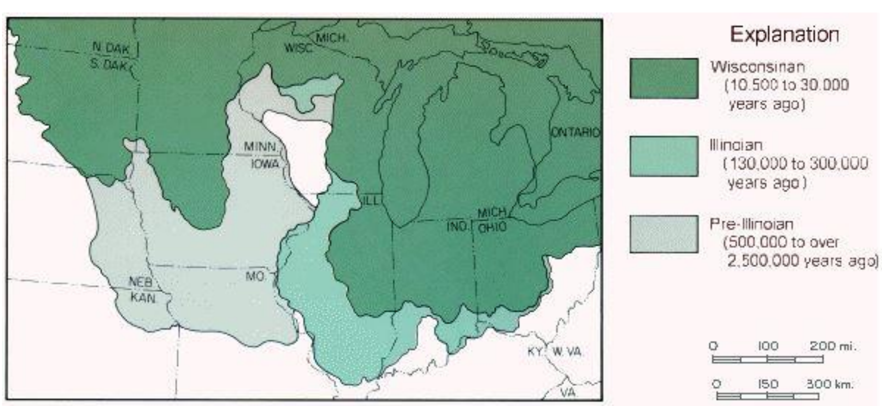

Figure 23 Glacial advances across the Upper Midwest. From Prior 1991

Figure 24 Pleistocene ice sheets at their maximum extensions from the three main centers. From Lee 1916.

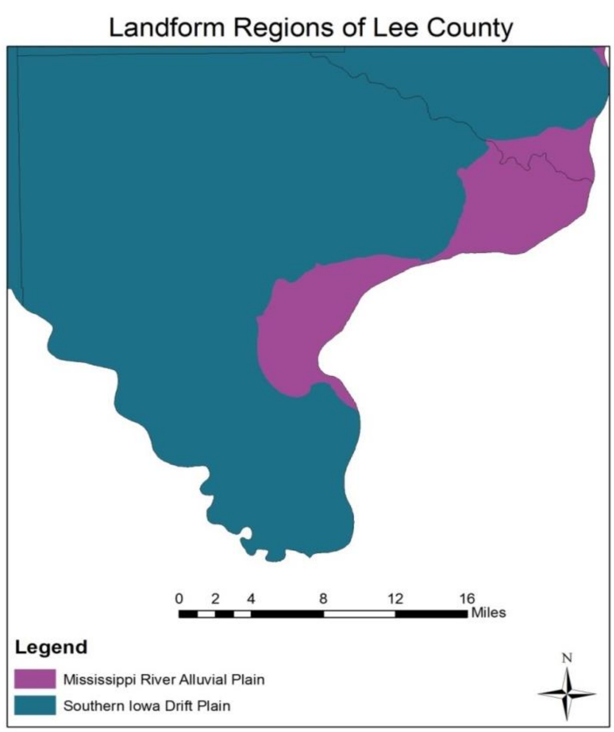

Figure 25 Landform regions of Lee County.

These Cenozoic deposits of Lee County make up two of the ten distinct landform regions in Iowa, those being the Southern Iowa Drift Plain and the Mississippi River Alluvial Plain (Figure 25). The group of Alluvial Plains makes up a relatively small area of Iowa's landform area. This landform region is created from rivers that make the distinctive, flat-floored corridors lain with thick deposits of alluvium (Figure 26). These deposits were originally created from glacial melt that formed these rivers and filled the valleys with layered deposits of clay, silt, sand, and gravel. The formation of the flat plains comes from the surrounding floodplains, which is the area surrounding the river that accumulates deposits during the river's flood stage. Being the most active and complex landforms, the alluvial plains can change size and shape depending on the river, the age of its valley, the type of geologic material the valley was carved from, and the fluctuations of the water (Prior 1991).

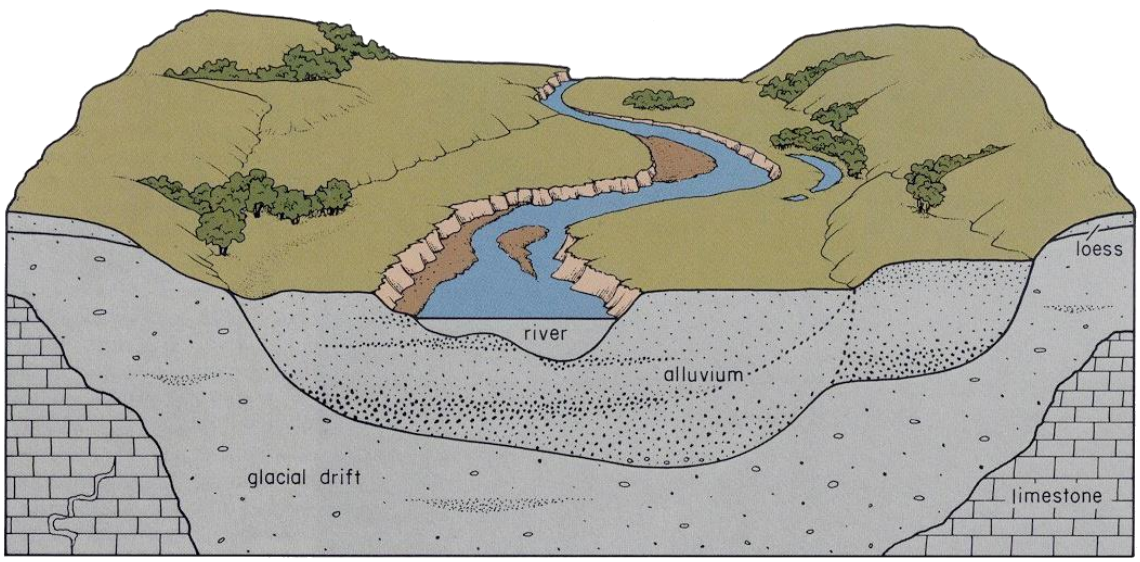

Figure 26 Cross-sectional example of Alluvial Plain. From Prior 1991.

Looking at the Southern Iowa Drift Plain, this is the typical landform people think of when they picture of Iowa's landscapes due to its size and location. This landform is the largest landform in Iowa, and it makes up most of the land that travelers of Interstate 80 see. Composition of the landform is mainly glacial drift brought in by the Pre-Illinoian Glacial Stage hundreds of thousands of years ago. This time allowed for erosion to take place and form well-established streams that have that carved into the landscape, giving the area its rolling hill topography (Figure 27). These streams pattern the area like the veins in a leaf. This branching network drained any wetlands left in the landform, removed any ice-contact landforms, and changed the original glacial plains into the present day rolling hills (Prior 1991). As the land was carved out by the flowing streams, a layer of loess was added to the surface. Thickness of the deposit varies, adding to the relief of the area. The bulk of this loess is called the Peoria Loess, which is the thick layer of loess seen within the county's drill cores.

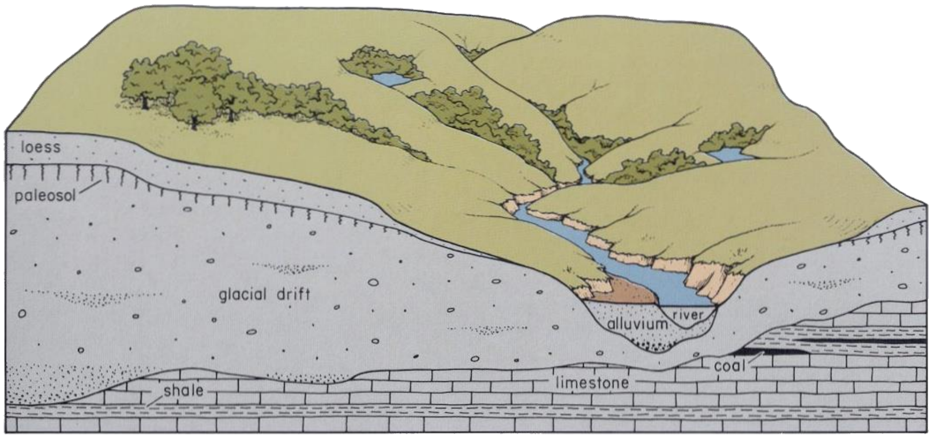

Figure 27 Cross-sectional example of Southern Iowa Drift Plain. From Prior 1991.

These two landform regions make up Lee County's surficial aquifers. These surficial aquifers can be broken up into three types, the alluvial aquifer, the drift aquifer, and the buried-channel aquifer (Figure 28). The highest yielding of these types is the alluvial aquifer, which lie within the Alluvial Plain. This is due to its loose sediment composition and rapid recharge rate. Yields can exceed 500 gallons per minute within this aquifer as seen in Figure 29. The only problem with this aquifer is that it poses the greatest contamination risk due to its contact with the Mississippi River. The drift aquifer and buried channel aquifer are contained within the drift of the Southern Iowa Drift Plain. The drift aquifers are composed of the glacial drift, and only yield water where beds of sand and gravel can be found, if it is silty and clayey water yield is low. Locally though, these beds of sand and gravel are thick and widespread enough to act as dependable water sources for private use. As for the buried channel aquifer, they are composed of alluvium that fills valleys that existed before the glacial period. These valleys were then

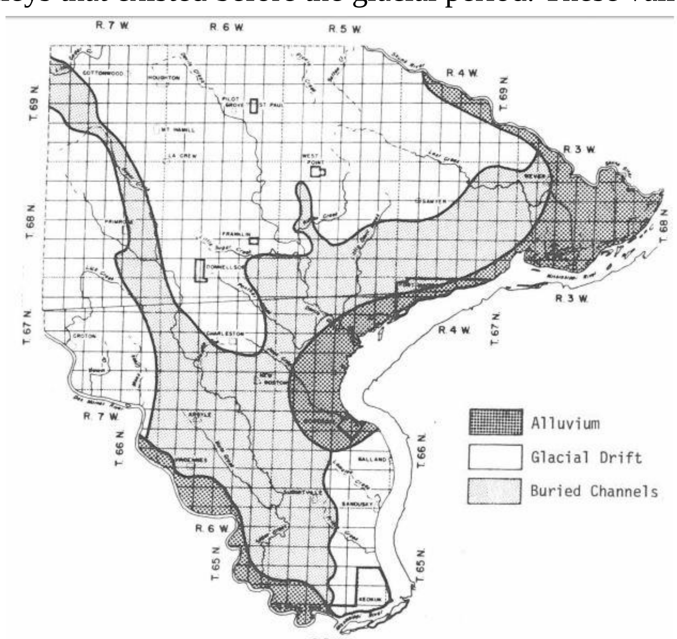

Figure 28 Map of surficial aquifers in Lee County. From Gordon 1980.

covered by till, but the alluvium still acts as an excellent aquifer yielding up to 100 gallons per minute. A map of wells across Lee County can be seen in Figure 30 with most private wells tapping into these alluvium and buried channel aquifers.

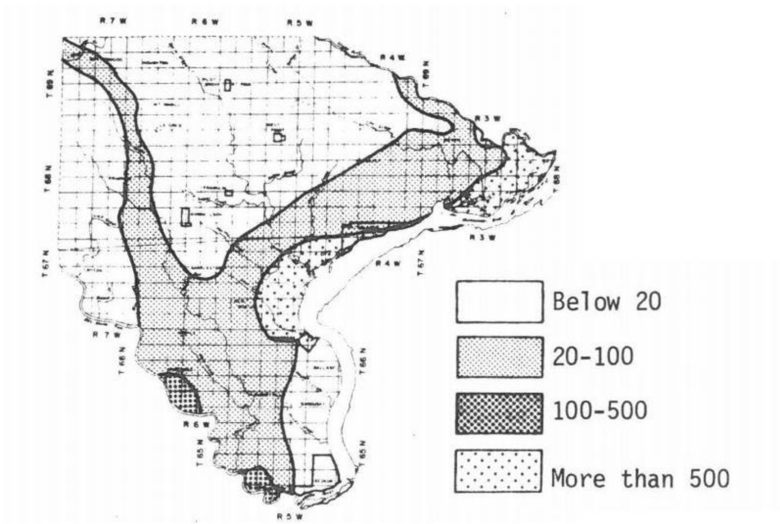

Figure 29 Map showing well yield from surficial aquifers. From Gordon 1980.

The Cenozoic of Lee County also includes its soils. For the most part these soils are rich and have a rich black A horizon to a depth of a few feet. Along the Alluvial Plains the soils tend to be sandier than those in the drift plain, but rarely are they to sandy to interfere with cultivation. The most prominent of the soil series in the county are the Lindley soils. They make up approximately 22 percent of the cover in the county as seen in Figure 31 (USDA 1979). These soils lie on the lower, convex side of slopes and are well drained. They consist of a surface layer that is about 10 inches thick of very dark grayish brown and yellowish brown loam. The soil then extends down about 60 inches, transitioning from the yellowish brown loam to yellowish brown clay loam (USDA 1979). These soils are not well suited for crop growth or building due to their relatively high slope. The soils on the other hand are extremely well suited for woodland and forested areas, therefore making up most of Lee County's wooded area.

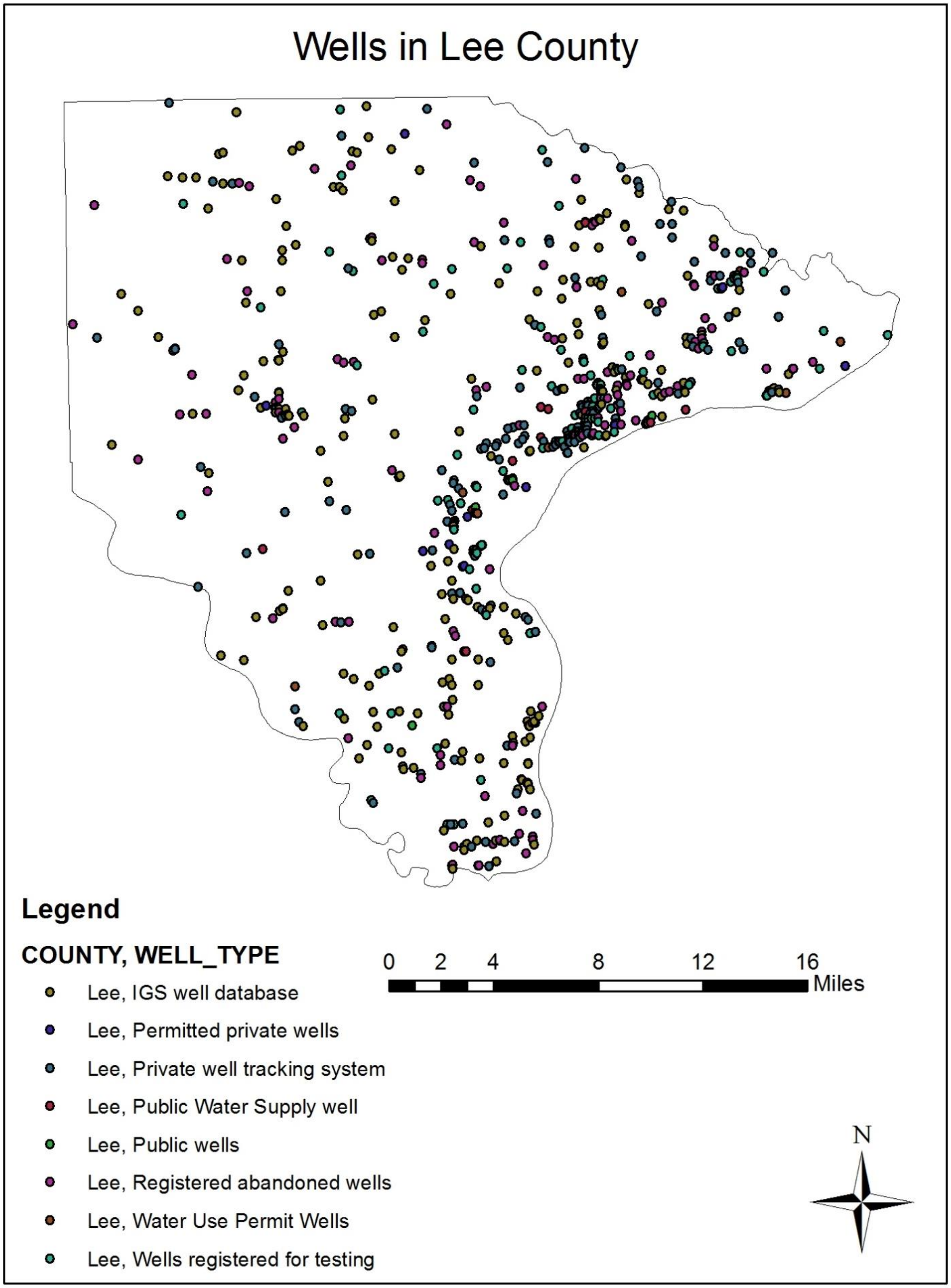

Figure 30 Map showing locations of wells throughout Lee County.

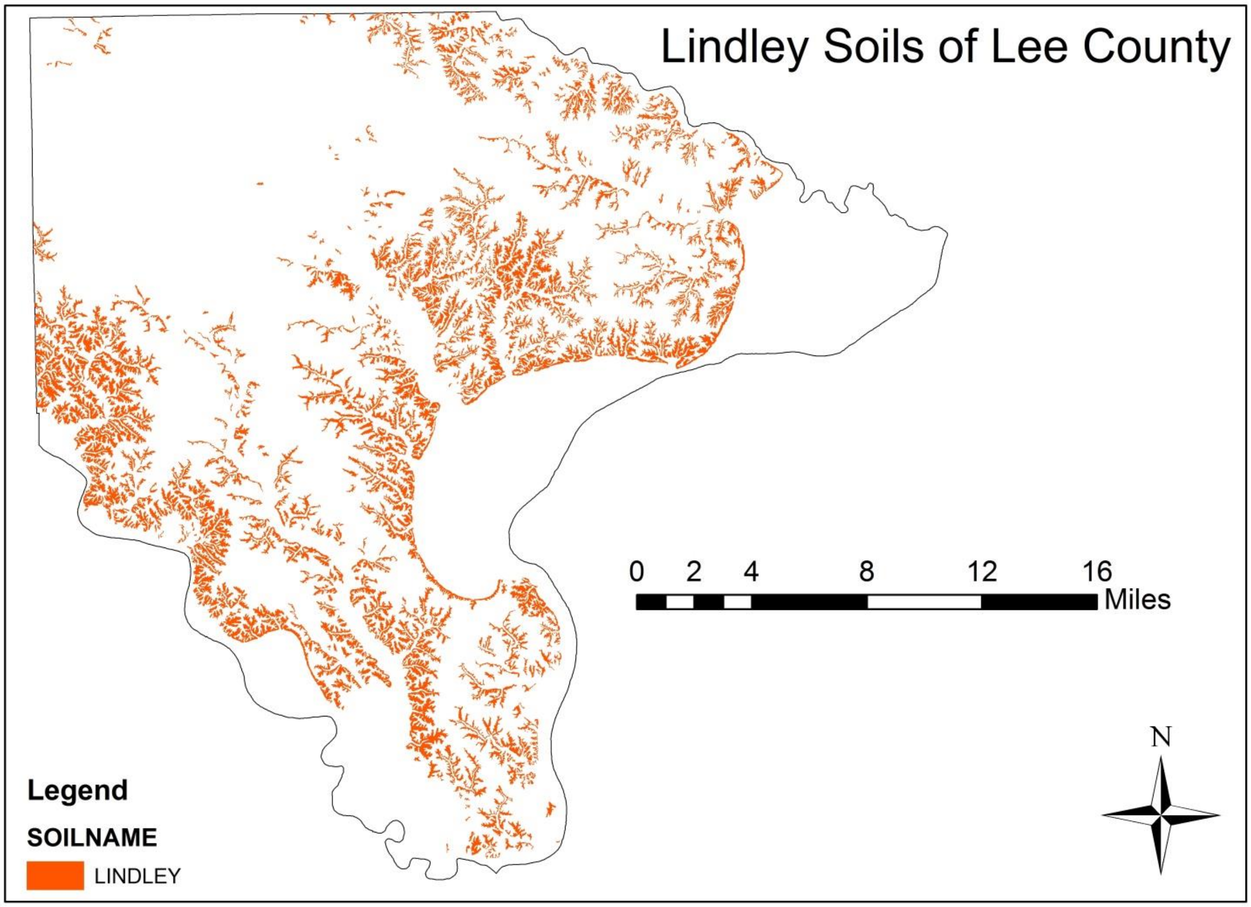

Figure 31 Distribution of Lindley soils throughout Lee County.

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