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CLASS VI PERMIT APPLICATION NARRATIVE 40 CFR 146.82(a)

Permit Application for One Proposed Class VI Injection Well

1 PROJECT BACKGROUND AND CONTACT INFORMATION

Carbon dioxide (CO_2) is the fourth-most common chemical in the Earth's atmosphere, but if concentrations become too high, it can cause adverse effects on the environment (Murray, 2019). According to the Emission Database for Global Atmospheric Research, global emission of CO_2 has increased more than 39% in the last century, since pre-industrial time. Global warming and climate change have sparked global efforts to reduce the concentrations of atmospheric CO_2 (Leung, Caramanna, & Maroto-Valer, 2014). For several decades, the federal government has strived to mitigate the release of greenhouse gases (GHGs) while using fossil energy, proposing carbon capture and storage (CCS) as a potential solution (Jones, 2020).

Geologic sequestration is the long-term containment of fluids within subsurface geologic formations to avoid its release into the atmosphere (Folger, 2018; Jones, 2020). Generally, CO_2 is injected as a dense fluid into a porous formation that has the capability to hold fluid. When injected at great depths, greater than about half a mile (2,640 feet), the pressure keeps the CO2 in its dense liquid state, reducing its probability of mitigation out of the geological formation (Folger, 2018).

The disposal of CO_2 via injection by Lorain Carbon Zero Solutions, LLC at the Lorain County Landfill will provide a safe alternative for CO_2 disposal. This environmentally friendly option could reduce the carbon footprint left by Lorain Carbon Zero Solutions, LLC.

An injection depth waiver or aquifer exemption expansion will not be requested for this project.

Table 1-1 provides the required administrative information for the Class VI injection well permit applications as required by 40 CFR 146.82 (e) (1 through 6).

2 SITE CHARACTERIZATION

Site characterization information required in the Class VI Permit Application is provided under 40 CFR 146.82(a), which includes information on the geologic and hydrogeologic characteristics used to develop a conceptual model of the proposed CO2 storage well at the Lorain County Landfill.

2.1 REGIONAL GEOLOGY, HYDROGEOLOGY, AND LOCAL STRUCTURAL GEOLOGY [40 CFR 146.82(A)(3)(VI)]

The regional stratigraphy and structural geology are outlined and discussed in the following sections per 40 CFR 146.82 (a) (3) (vi).

The regional geologic evaluation covers Ohio, with emphasis on northern Ohio. Regionally, the Lorain County Landfill is located approximately 33 miles southwest of Cleveland, Ohio. The Lorain County Landfill and surrounding area is depicted on Figure 2-1. A regional geologic map of Ohio is depicted on Figure 2-2.

2.1.1 STRATIGRAPHY

A generalized column of bedrock units in Ohio is provided in Figure 2-3. The relevant formations will be discussed below in detail from depth to surface, regionally.

PRECAMBRIAN GRANITE

The known Precambrian history of Ohio began approximately 1.4 to 1.5 billion years ago, during the emplacement of a 7-mile thick layered sheet of granite and rhyolite, caused by an uprising in the Earth's mantle, known as a superswell. This event formed what is now commonly referred to as the Granite-Rhyolite Province. The coarse grained igneous granite formed at depth while the fine-grained rhyolite formed near the surface (Hansen M. C., 1997).

Continued doming of the continental crust from the superswell caused the crust beneath Ohio to extend and split, known as rifting, which created major faulting and complex river basins. About 1 billion years ago, the doming ceased, along with the associated processes occurring at that time. Between 990 and 880 million years ago, a continent to the east collided with the North American craton. At this time, eastern Ohio marked the edge of the North American craton. The collision created crustal compression and the development of the mountain range now referred to as the Grenville Mountains. During this collision, the rocks were folded, twisted, and metamorphosed. About 300 million years ago, after the formation of the Grenville Mountains, a long period of erosion occurred, reducing the landscape to gentle slopes (Hansen M. C., 1997).

Despite the span of time that the Precambrian represents, it is the most poorly known geologic unit in Ohio. These predominately crystalline igneous and metamorphic rocks are buried deeply beneath the subsurface at depths ranging from approximately 2,500 feet in western Ohio to approximately 13,000 feet in southeastern Ohio (Hansen M. C., 1997).

The first well drilled to the depth of the Precambrian in the state of Ohio was the D. L. Norris well in Hancock County in 1912, approximately 100 miles west southwest of Lorain County, Ohio. Only 11 more wells in Ohio were drilled into the Precambrian during the next 43 years. Since, there has been a steady increase in deep-drilling activity throughout Ohio (Summerson, 1962). Commonly the Precambrian unit is refered to as "granite" in reference to a common rock type found (Hansen M. C., 1997), as well as "crystalline", "basement", and "basement complex" interchangeably. The Precambrian rocks have been collected and described in various wells across Ohio in well cuttings, finding a variety of igneous and metamorphic rock (Summerson, 1962).

Most of the igneous rocks identified in Ohio are predominantly granite and related rocks, such as rhyolite and diorite. They typically contain various other minerals, including orthoclase, oligoclase, plagioclase, quartz, potassium feldspar, andesine, and epidote, with small amounts of biotite, hornblende, magnetite, hematite, pyrite, zircon, garnet, leuocoxene, tourmaline, apatite, hypersthene, and augite. Most of the metamorphic rocks identified in Ohio are either metamorphosed sedimentary rocks and metamorphosed basic igneous rocks. The metamorphosed sedimentary rocks generally consist of labradorite, hornblende, hypersthene, biotite, hematite, chlorite, and garnet. Another group of metamorphosed rocks include gneiss and some schist. There is considerable variation in these rocks throughout the well samples taken from Ohio. Many samples contained banded units; the lighter bands consist of orthoclase, microcline, quartz, muscovite, and biotite, and the darker bands consist of plagioclase, hornblende, biotite, and chlorite (Summerson, 1962). This Precambrian unit forms a stable, base or craton of continental plates (Mudd, Johnson, Christopher, & Ramakrishnan, 2003).

These rocks are generally referred to "basement" rocks because they provide the foundation of the overlying Paleozoic rock units. The close of the Precambrian was marked by the advance of the Cambrian seas (Hansen M. C., 1997).

MT. SIMON SANDSTONE

The basal Cambrian rock unit beneath most of Ohio, which directly overlies the Precambrian unit, is the Mt. Simon Sandstone. It was deposited during the formation of the Iapetus Ocean, when prehistoric Ohio was located on the stable, passive margin of Laurentia, the North American Craton (Hansen, 1998). The Mt. Simon Sandstone consists of fine-grained to conglomerate sandstone, often poorly consolidated, with few areas containing siliceous cement (Janssens, 1973).

Regionally, the sediments of the Mt. Simon Sandstone have high porosity and permeability and is often used for underground waste disposal across the Midwest (Hansen, 1998; Mudd, Johnson, Christopher, & Ramakrishnan, 2003). In a study performed by Janssens (1973), permeability and porosity data was collected via core analysis of four storage wells injecting into the Mt. Simon Sandstone. The four wells are located in Allen County, Butler County, Richland County, and Scioto County (Figure 2-2). The average porosity of the Mt. Simon Sandstone of the four well analysis was approximately 13% (Janssens, 1973).

The well nearest to the Lorain County Landfill, found in Richland County, was evaluated in detail to estimate conditions of the Mt. Simon Sandstone locally near the site. [redacted] (md) (Janssens, 1973).

Medina and Rupp (2012) performed a different study to investigate the reservoir characterization and lithostratigraphic division of the Mt. Simon Sandstone. Their study area is comprised of parts of Kentucky, Indiana, Illinois, Michigan, and Ohio, which show evidence of the vast lateral extent of the Mt. Simon Sandstone throughout the region. The thickness of the Mt. Simon Sandstone ranges in thickness from between 2,301-2,600 feet in central eastern Illinois, and thins to the east across Indiana and Ohio, to less than 200 feet in eastern Ohio (Medina & Rupp, 2012). This regional trend is illustrated on Figure 2-4 (Janssens, 1973). Locally, the Mt. Simon Sandstone is estimated to be between 100 and 200 feet thick around the Lorain County Landfill (Figure 2-4) (Janssens, 1973).

The lithostratigraphic divisions of the Mt. Simon Sandstone were interpreted from a well in Porter County, Indiana, more than 250 miles west of Lorain County, OH, describing the Mt. Simon Sandstone as three distinct units based on geophysical logs. [redacted]

[redacted] (Mudd, Johnson, Christopher, & Ramakrishnan, 2003). The Mt. Simon Sandstone underlies with gradual contact to the Eau Claire Formation and its equivalent formations (Janssens, 1973).

EAU CLAIRE FORMATION AND EQUIVALENT

The Mt. Simon Sandstone is overlain by the Eau Claire Formation in western Ohio and by the Rome Formation and Conasauga Formation, in ascending order, in eastern Ohio (Figure 2-3). The geographic boundary between the Eau Claire Formation and the Rome Formation is provided in Appendix 2-1, showing the mappable unit thickness of the Eau Claire across western Ohio. Where it is not shown in eastern Ohio, the Eau Claire is not observed. The Kerbel Formation overlies parts of the Eau Claire Formation and the Conasauga Formation in central Ohio (Figure 2-3) (Janssens, 1973).

The Rome and Conasauga Formation is the proposed confining zone for the Lorain County Landfill. Locally, the Rome Formation directly overlies the Mt. Simon Sandstone in eastern Ohio (Figure 2-3), including Lorain County (Janssens, 1973).

The Eau Claire Formation is composed of a low porosity crystalline dolomite, sandy dolomite, dolomitic and feldspathic sandstone, siltstone and shale (Wickstrom, et al., 2005). The contact between the Mt. Simon Sandstone and the Eau Claire Formation can be found at the base of a glauconitic to very glauconitic very fine and fine-grained sandstone (Janssens, 1973). The Eau Claire Formation contact with the Mt. Simon Sandstone is typically gradational, representing gradual facies changes from near shore marine Mt. Simon to less siliciclastic marine environments of the Eau Claire Formation (Medina & Rupp, 2012). The Eau Claire Formation ranges in thickness within the region from approximately 562 feet in Defiance County in northwest Ohio to approximately 200 feet to the east in northern Lucas County (Janssens, 1973).

As the Iapetus Ocean continued to flood the North American Craton, the waters deepened, allowing for the accumulation of the carbonate sediments of the Rome and Conasauga Formations in parts of Ohio (Hansen, 1998). The contact between the Rome Formation and the Mt. Simon Sandstone can be found at the base of an oolitic and pelletal sandy to very sandy dolomite with minor interbedded sandstone, typically gradual (Janssens, 1973).

The Rome formation predominately consists of dolomite (Janssens, 1973) and considered impermeable, excluding the various interbedded sand intervals (Wickstrom & Baranoski, 1993). Sensitive, Confidential, or Privileged Information [redacted]

In eastern Ohio, directly overlying the Rome Formation, is the Conasauga Formation, consisting of shale with minor interbedded carbonate, siltstone, and sandstone. Eastward from central Ohio, the Conasauga Formation gradually transitions into a sandy dolomite. Sensitive, Confidential, or Privileged Information [redacted]

The estimated low porosity and permeability observed near Lorain County Landfill within the Rome and Conasauga Formations, result for impermeable units ideal for confinement of CO_2 for the proposed Class VI injection well (Wickstrom & Baranoski, 1993; Gupta, et al., 2017).

The Kerbel Formation overlies parts of the Eau Claire Formation and the Conasauga Formation in central Ohio, which consists of upward-coarsening dolomitic sandstone (Janssen, 1973), interpreted to be a wedge of deltaic sediments (Hansen, 1998). The Kerbel Formation ranges in thickness from approximately 0 to 170 feet, with the greatest thickness generally found in Wood and Sandusky Counties. The Kerbel Formation is estimated to be approximately 50 feet locally around the Lorain County Landfill (Appendix 2-2) (Janssens, 1973). The porosity determined from petrophysical methods ranged from 0-0.18%, the average porosity determined to be approximately 0.06% (Gupta, et al., 2017). The thin Kerbel Formation layer present near the Lorain County Landfill provides an additional buffer zone to confine the CO_2 injectate from vertical migration (Wickstrom & Baranoski, 1993).

THE KNOX DOLOMITE

The Knox Dolomite is laterally extensive across Ohio, covering the Eau Claire Formation in western Ohio, the Kerbel Formation in central Ohio, and the Conasauga Formation in eastern Ohio (Figure 2-3). The Knox Dolomite is often considered part of the Trempealeau, which is dolomitized limestone found throughout most of Ohio, marked by the Knox Unconformity (Cramer, 1990). In 1964, hundreds of wells were completed in this formation near Lorain County in Morrow County, Ohio. The core properties measured from these wellbores revealed an average porosity of 7.8% and an average permeability of 49 md. These cores also indicated that a significant network of natural fractures exists (Sutton, 1965).

The Knox Dolomite is considered the lower unit of the Trempealeau Formation. The Trempealeau's porosity is secondary, created from dolomitization and dissolution. Average thickness of the Trempealeau is approximately 300 feet and vugular porosity is as high as 30% in its upper zones (Cramer, 1990).

The Knox Dolomite sits beneath a major unconformity known as the Knox Unconformity (Hansen, 1998), seen throughout the state of Ohio. This unconformity is interpreted as the base unit of the Ordovician in Ohio (Hansen M. , 1997). The Knox Unconformity, in places, represent a hiatus of non-deposition and/or erosion of approximately 30 to 40 million years (Brett & Algeo, 1999). The Knox Unconformity is easily recognizable in eastern Ohio on geophysical logs due to the sudden lithologic change from the Knox Dolomite below and the Wells Creek Formation (Ryder, Harris, & Repetski, 1992).

WELLS CREEK FORMATION

After the erosion that created the Knox Unconformity, the seas returned with the deposition of the Lower Ordovician Wells Creek Formation, which consists of shale, dolomite, and often basal sandstone (Ryder, Harris, & Repetski, 1992). Samples taken from the Wells Creek Formation in various wells in northwest Ohio contained waxy, dolomitic, pyritic green shales; argillaceous limestones and dolomites; brown, gray and black shales; and small amounts of sandstone and siltstone (Wickstrom, Gray, & Stieglitz, 1992). The Well Creek Formation is often referred to as the Glenwood and St. Peter Sandstone (Figure 2-3).

The impermeable shale and siltstone (Janssens, 1973) has high variably in thickness across the area due to it being deposited on the irregular surface of the Knox Unconformity (Wickstrom, Gray, & Stieglitz, 1992). The Wells Creek Formation is nonexistent in some areas up to 60 feet thick to the east, averaging approximately 20 feet regionally (Wickstrom, Gray, & Stieglitz, 1992; Hansen M. C., The Geology of Ohio - The Ordovician, 1997). In regards to petroleum geology, the Wells Creek Formation acts as a seal rock for hydrocarbon reservoirs of the Knox Group (Wickstrom, et al., 2005).

The contact between the Wells Creek Formation and the overlying Black River Group is generally sharp and well defined. The lithology changes from the shales and argillaceous (dirty) carbonates to clean limestone and dolomite (Wickstrom, Gray, & Stieglitz, 1992).

BLACK RIVER GROUP

The Black River Group consists of uniform lithology across the region (Patchen, et al., 2005), primarily fine-grained tan and gray limestone (Hansen M. C., The Geology of Ohio - The Ordovician, 1997), often micritic and pelletal, with some dolomitic and argillaceous zones (Wolfe, 2008). Clear crystalline calcite fills fenestrae in parts of the Black River Limestone (Wickstrom, Gray, & Stieglitz, 1992). Fossils are not abundantly found within this formation, but they can be found in localized areas (Wickstrom, Gray, & Stieglitz, 1992; Patchen, et al., 2005). These fossil zones identified in cores show that burrows and mottling are common, including brachiopods, ostracodes, gastropods, mollusks, trilobites, and coral (Wickstrom, Gray, & Stieglitz, 1992). Chert is also present in various areas regionally, but generally near the top of the formation (Wickstrom, Gray, & Stieglitz, 1992; Patchen, et al., 2005).

The thickness of the Black River Group is approximately 300 feet in northwestern Ohio, in Williams, Defiance, and Paulding Counties, and thickens eastward to more than 500 feet, in Huron and Richland Counties (Wickstrom, Gray, & Stieglitz, 1992; Hansen M. C., The Geology of Ohio - The Ordovician, 1997). The depth of the top of the Black River Group ranges from approximately 700 feet adjacent to Ohio, Little Miami, and Great Miami Rivers, to more than 2,000 feet in Champaign County (Wolfe, 2008).

The Black River Group was deposited in a shallow epeiric-sea environment, ranging from shallow subtidal to supratidal environments in northwest Ohio. This depositional environment was common in this region throughout the Cambrian and Ordovician Periods. (Wickstrom, Gray, & Stieglitz, 1992). The diachronous contact of the Black River Group and the overlying Trenton Limestone is a gradual, interlayered zone that is approximately 10 feet thick (Patchen, et al., 2005).

TRENTON LIMESTONE AND EQUIVALENT

In general, the Trenton Limestone consists of an abundance of whole or fragmented fossils within a fine to coarse grained, gray to brown limestone. The most common fossils found within the formation are brachiopods, bryozoans, crinoids, ostracodes, with few trilobites, pelecypods, and gastropods (Wickstrom, Gray, & Stieglitz, 1992). The middle of the formation is often less crystalline, comparatively, and lenses of gray and white chert are often present at the base of the formation (Calvert, 1962). Thin black shale beds and bentonite layers are commonly found in particular beds within the formation (Wickstrom, Gray, & Stieglitz, 1992), as well as an abundance of zones with secondary dolomitization (Hansen M. C., The Geology of Ohio - The Ordovician, 1997).

The Trenton Limestone does not outcrop at the surface in Ohio (Hansen M. C., The Geology of Ohio - The Ordovician, 1997), but ranges in thickness regionally from approximately 40 feet in Champaign and Miami Counties in southern Ohio to approximately 300 feet in Ottawa and Lucas Counties in northern Ohio. In contrast to the underlying Black River Group, the orientation of strike of the Trenton Limestone is dominantly northeast-southwest (Wickstrom, Gray, & Stieglitz, 1992).

There are three distinct depositional environments of the Trenton Limestone throughout Ohio, which are platform, platform margin, and open shelf (Wickstrom, Gray, & Stieglitz, 1992). The depositional environment in which the Trenton Limestone was deposited was deeper than that of the Black River Group, thought to be the result of tectonic activity associated with the Taconic Orogeny (Hansen M. C., The Geology of Ohio - The Ordovician, 1997). The marine transgression from southeast to northwest blur both the vertical and lateral contact between these distinct depositional environments; they often grade from one to other vertically and laterally throughout the region (Wickstrom, Gray, & Stieglitz, 1992).

The thin basal open-shelf facies of the Trenton Limestone occupy the full thickness of the formation in southeastern Ohio. These facies are transitional between the shallower, restricted depositional environment of the underlying Black River Group and the shallow, open-marine platform facies of the Trenton Limestone to the northwest. The interlayed character of the various textures within the lower open-shelf facies indicates a combination of periods of storm induced, high energy deposition and calm water deposition on minor topographic shifts of the sea floor. The thickness of the open-shelf facies range from approximately 20 to 100 feet and primarily consists of wispy to nodular-bedded, gray to brown bioclastic limestone with wackestone and packstone, and minor amounts of interlayered mudstone and grainstone. Fossils are found throughout the open-shelf facies, which include brachiopods and bryozoans, with less crinoids and trilobites. Ostracodes are abundant, and concentrated in the top of the formation to the south and east (Wickstrom, Gray, & Stieglitz, 1992).

The second primary facies of the Trenton Limestone, the platform facies, overlies the basal open-shelf faces in central Ohio, oriented northeast to southwest. The platform facies was deposited in shallow, open, normal-marine conditions common to carbonate platforms, when currents and wave action were strong enough to winnow out the carbonate muds and break up the fossils found within this facies. The interlayered wackstone and shale intervals either represent deep water deposition or areas that were protected on the platform, both low every environments. The platform facies occupy the majority of the thickness of the Trenton Limestone in central Ohio, ranging in thickness from approximately 100 to 225 feet and primarily consists of light to dark brown grainstone and packstone, commonly massively bedded, with small amounts of wavy dark shale layers. Fossils are found in these facies, including primarily brachiopods and crinoids, with rare bryozoans and trilobites. Due to the abundance of the Brachiopods and crinoids, it often formed thick sequences of brachiopodsal-crinoidal grainstone, when represent the platform-edge sands and local bars that shifted on the shallow sea floor (Wickstrom, Gray, & Stieglitz, 1992).

The third primary facies of the Trenton Limestone, the platform-margin facies, is found in northwest Ohio, thickening from Darke County to Ottawa County. The platform-margin facies is thought to have developed contemporaneously with the Point Pleasant deposition to the south and east. This gentle slope formed on the platform margin represented a transitional zone between the deeper basinal water to the southeast and the shallow water to the northwest. These facies have high variability in thickness and rock type due to the high susceptibility to sea-floor disturbances by waves and storms during its deposition. The rock types range from lime mudstone to grainstone. Fossils commonly found in the other Trenton Limestone facies can be found within the platform-margin facies, thought to have been washed into the facies, characterized by scour features, lag concentrations of fossils, and lithoclasts (Wickstrom, Gray, & Stieglitz, 1992).

The Trenton Limestone was once an important economic unit in Ohio for the production of oil and gas (Wickstrom, Gray, & Stieglitz, 1992; Hansen M. C., The Geology of Ohio - The Ordovician, 1997). The original limestone experienced secondary dolomitization, which created intercrystalline, interparticle, moldic, and vuggy porosity. The location of the porosity created from the dolomitization became essential when exploring hydrocarbon reservoirs in the Trenton Limestone (Wickstrom, Gray, & Stieglitz, 1992).

In southwest Ohio and parts of northeast and southeast Ohio, the Trenton Limestone equivalents are found, in ascending order, the Lexington Limestone and the Point Pleasant Formation (Figure 2-3). The Trenton/Lexington and the overlying Utica/Point Pleasant units are some of the most complex boundaries in the region. The Trenton/Lexington grades upward to dominantly dark gray, brown, then black platy, finely laminated, calcareous Utica Shale (Patchen, et al., 2005) and interbedded calcareous gray shales and limestones of the Point Pleasant Formation (Patchen, et al., 2005; Hansen M. C., The Geology of Ohio - The Ordovician, 1997). The Point Pleasant Formation can be seen outcropped along the Ohio River (Hansen M. C., The Geology of Ohio - The Ordovician, 1997).

CINCINNATI GROUP

The Upper Ordovician of North America is the Cincinnatian Group (Ausich, 1999), which are exposed in parts of Ohio, Indiana, and Kentucky (Brame & Stigall, 2014; Smrecak & Brett, 2014). The Cincinnatian Group was named for its rich, fossiliferous beds, containing bryozoans, brachiopods, trilobites, echinoderms, crinoids, asteroids, cyclocystoids, edioasteroids, rhombiferans, and stylophornas. There are more than approximately 37 species assigned to 20 genera recognized from the Cincinnati strata. In comparison with the Middle Ordovician fossils, the assemblages found in the Upper Ordovician strata contains different characteristics. The blastozoians are very rare and calceocrinoids and hybocrinid, generally abundantly found with the Middle Ordovician strata, are absent. The crinoid assemblages also lack diversity, generally containing less than five species but occurring in densities as high as 400 per square metre (Ausich, 1999). Due to the abundance, diversity, and preservation of the fossils found within the Cincinnatian Group, they have been extensively studied (Brett & Algeo, 1999; Brame & Stigall, 2014; Dattilo, Brett, Tsujta, & Fairhurst, 2008; Smrecak & Brett, 2014; Kirchner & Brett, 2008)

These sediments were thought to have been deposited in a shallow-marine subtropical environment. During the middle Ordovician, the eastern edge of the North American craton collided with various island arcs and microcontinental terranes (Brett & Algeo, 1999). Most of the terrigenous sediment that accumulated in the Cincinnatian Group derived from the rising Taconic Mountains to the east (Dattilo, Brett, Tsujta, & Fairhurst, 2008) and northeast (Brett & Algeo, 1999), and carbonate grains were derived locally (Brame & Stigall, 2014). Large tropical storms frequently disturbed the sediments accumulating on the seafloor during the Cincinnatian Group deposition (Brame & Stigall, 2014; Holland, Miller, Dattiol, Meyer, & Diekmeyer, 1997), resulting in thicker, more abundant siliciclastic layers in deeper-water environments, and shelly limestone beds in shallow-water environments (Brame & Stigall, 2014).

The Cincinnati Group can be subdivided into six well developed, depositional sequences (Brame & Stigall, 2014; Brett & Algeo, 1999), compromised in three different stages, the Edenian, Maysvillian, and Richmondian stages (Brett & Algeo, 1999). Smrecak and Brett (2014) identify the formations designated in each stage: Kobe Formation (Edenian stage), Fariview Formation and Great Lake Formation (Maysvillian stage), and Arnheim Formation, Waynesville Formation, Liberty Formation, and Whitewater Formation (Richmondian stage).

Within each sequence, the facies can be distinguished and referred to as system tracts. These system tracts include the lowstand system tract, transgressive system tract, and highstand system tract. The facies found within the lowstand system tract are typically shallow-water, non-marine channel fillings. Deepwater turbidite fans are also considered potentiall lowstand system tract accumulations during times the sediments were flushed from shallow water to deep water environments. The facies found within the transgressive system tract show a deepening upward, retrogradational pattern of smaller scale cycles, bounded by the surface of maximum flooding. The facies found within the highstand systems tract are typically deeper-water dark shales that sharply overlie the maximum flooding surface (Brett & Algeo, 1999). Each of the six identified sequences consist of a thin transgressive systems tract overlain by thick shallowing-upward highstand systems tract. The amount of shale within each sequence decreases upward as well (Brame & Stigall, 2014).

QUEENSTON SHALE

At the end of the Ordovician Period, fine-grained clastic sediments, mixed with coarser sediments, were eroded from the Tectonic Orogeny and carried westward (Aucoin & Brett, 2015). A complex delta system of mud was discharge into the shallow seas that covered Ohio and the nearby areas (Hansen M. C., The Geology of Ohio - The Ordovician, 1997). The Clastic wedge prograded westward, covering all of Ohio, and reaching east-central Kentucky and Ohio (Brett & Algeo, 1999). The Queenston Shale is locally referred to as the “Medina” (Janssens A. , 1977), and often described as a distinct red shale (Brett & Algeo, 1999; Janseens, 1968).

The top of the Upper Ordovician Cincinnatian Group and Queenston Shale in some parts of the state, is bounded by a unconformity known as the Cherokee Unconformity. The Cherokee Unconformity represents a hiatus of non-deposition and or erosion of approximately 3 to 4 million years. This major unconformity is typically attributed to major lowstand or a global drop in sea level (Brett & Algeo, 1999) due to continental glaciations (Ausich, 1999).

CLINTON FORMATION

The Clinton Formation marks the beginning of the Silurian Period, a time of relative tectonic quiescence after the Tectonic Orogeny. The remnants of the Tectonic Orogeny could still be found to the east of Ohio, although chemical rocks dominated Ohio during the Silurian Period. The chemical rocks include limestone, dolomite, gypsum/anhydrite, and halite, which indicate the large distance from any uplands or elevated terrain. The erosion of the uplands from the Tectonic Orogeny resulted in deposition of sandstone and conglomerates in New Jersey, New York, and eastern Pennsylvania, but by late Silurian, those areas were also dominated by chemical rocks, similar to those found over Ohio (Hansen M. C., Geology of Ohio - The Silurian, 1998). The Clinton Formation is thought to have been deposited in a fluvial-deltaic environment, due to the sediments being carried from the uplands via rivers, and deposited into the shallow seas that covered Ohio (Haneberg-Diggs, 2015).

In Ohio, the informal name, "Clinton" Formation, to discuss units within the cataract Group (Riley, Wicks, & Perry, 2010) is used. The informal name "Clinton" in 1887 (Boswell, Pool, Pratt, & Matchen, 1993) because the formation was originally correlated to a unit in New York with the same name (Boswell, Pool, Pratt, & Matchen, 1993; Hansen M. C., Geology of Ohio - The Silurian, 1998). The Clinton is also subdivided into various units including the Medina Sand, Red Clinton, White Clinton, and the Stray Clinton (Riley, Wicks, & Perry, 2010).

The base of the Silurian system in Ohio is identified by the highly fossiliferous limestone of the Brassfield Formation that overlies the regional Cherokee Unconformity that covers Ohio (Hansen M. C., Geology of Ohio - The Silurian, 1998). The Brassfield Formation is often referred to as the "Medina Sand" (Riley, Wicks, & Perry, 2010). The Medina is the first sequence identified within the Brassfield Formation (Brett & Algeo, 1999). In northwestern and eastern Ohio, the dominate rock type of the Brassfield Formation and its equivalent is dolomite (Hansen M. C., Geology of Ohio - The Silurian, 1998).

The Clinton Formation generally consists of medium-fine grained, quartzose interbedded sandstone, siltstones, and shales, with small amounts of carbonates (Wickstrom, Slucher, Baranoski, & Mullett, 2008; Riley, Wicks, & Perry, 2010). The variability in color of the sandstone found within the Clinton Formation ranges from white to gray to red, which resulted in the various subunits referred to by drillers. Most of the Clinton Formation is well cemented with silica (quartz). The growth of the quartz, along with carbonate and clay materials, reduced the primary porosity within the unit. Secondary porosity is present and resulted from dissolution of unstable cement minerals (Riley, Wicks, & Perry, 2010). The measured effective porosity from geophysical logs in the net sand intervals generally range from 5 to 14%. The permeability of this unit varies, but generally ranges from less than 0.1 md to 40 md. In eastern Ohio, the Clinton Formation can reach 200 feet thick, and increases eastward (Wickstrom, Slucher, Baranoski, & Mullett, 2008).

The power of natural gas from the Trenton Limestone at Findlay in 1884 lead to the discovery of the gas within the Clinton Formation. The first large discoveries occurred in 1889, with two high volume wells. This discovery resulted in tens of thousands of wells into hundreds of oil and gas fields throughout eastern Ohio, some still being used today as a source of hydrocarbons, gas storage, waste disposal, and enhanced oil recovery (Haneberg-Diggs, 2015). Since the 1970's, the Clinton Formation has been the most drilled horizon in Ohio (Wickstrom, Slucher, Baranoski, & Mullett, 2008).

The top of the Clinton Formation is marked by another regional unconformity identified by the "Packer Shell" at the base of the Dayton Formation (Riley, Wicks, & Perry, 2010).

CLINTON GROUP

The Clinton Group includes the Dayton Limestone and the Rochester Shale (Figure 2-3). The Dayton Formation and the Rochester Shale was deposited over a regional unconformity, during a marine transgression (Casey, 1996).

The Dayton Formation consists of coarsely crystalline, medium bedded dolomite (Casey, 1996), light-yellowish-gray to light-yellowish-brown, and slightly glauconitic. Dayton Stone was originally used in 1871 to identify exposures of about five feet of fine-grained limestone located in Montgomery, Ohio. Over time, it was referred to as the Dayton Limestone, then the Dayton Formation due to the dolomite content in the unit. The contact from the limestone of the Dayton Formation to the shale of the Rochester Shale is often distinct and identifiable (Janseens, 1968).

The Rochester Shale consists of soft calcareous clay shale (Casey, 1996), often gray, greenish-gray, green, dark-brown, and dolomitic (Janseens, 1968), with then layers of dolomite (Casey, 1996), often light-medium greenish-gray to brownish-gray dolomite (Janseens, 1968).

BIG LIME

The thick carbonates above the Clinton-Medina Sandstones are locally referred to as the "Big Lime" (Wickstrom, Slucher, Baranoski, & Mullett, 2008). The informal groupingincludes in ascending order, the Lockport Group, Salina Group, Bass Island Formation, Helderberg Limestone, Oriskany Sandstone, Bois Blanc Formation, and the Onodaga Limestone (Figure 2-3).

Overlying the Rochester Shale is the Lockport Group (Hansen M. C., Geology of Ohio - The Silurian, 1998). The name "Lockport" was used by Hall in 1839 to identify exposed limestone found in Lockport, New York. The Lockport Group is also exposed in western Ohio (Janseens, 1968). The Lockport Group consists of the Lockport Dolomite in eastern Ohio (Hansen M. C., Geology of Ohio - The Silurian, 1998; Wickstrom, Slucher, Baranoski, & Mullett, 2008), generally consisting of a massive marine, gray, dolomite (Wickstrom, Slucher, Baranoski, & Mullett, 2008; Janseens, 1968), approximately 150 to 200 feet thick. The Lockport Group can be subdivided into the Bisher Formation, Lilley Formation, and the Peebles Dolomite in southern Ohio. It can be subdivided into the Euphemia Dolomite, Springfield Dolomite, and the Cedarville Dolomite in western Ohio.

The Lockport Group was deposited in the Silurian Period, during a time of extensive reef building in Ohio and nearby areas. Reefs preserve the skeletal framework and materials accumulated by a wealth of organisms present and concentrated in the sea in certain areas, abundantly found in the Great Lakes area (Hansen M. C., Geology of Ohio - The Silurian, 1998). In central and eastern Ohio, a high porosity zone found within the Lockport Dolomite is locally referred to as the "Newburg" sandstone (Gupta, 2008; Wickstrom, Slucher, Baranoski, & Mullett, 2008). The Newburg is thought to be associated with patch reef development (Wickstrom, Slucher, Baranoski, & Mullett, 2008).

The Salina Group was used originally in 1863 to identify salt beds found in Cayuga and Onondaga Counties, New York. Since then, the formation has been redefined several times (Janseens, 1968). The Salina is currently subdivided into seven units, designated as A to G is ascending order (Janseens, 1968; Hansen M. C., Geology of Ohio - The Silurian, 1998). These units are also identified and shown on Figure 2-3. The Salina Group consists of dense to microcrystalline gray and brown dolomite. It is often interbedded with evaporates such as anhydrite, gypsum, or halite, among small amounts of limestone, and gray and brown shale, depending on the unit within the Salina Group (Janseens, 1968; Hansen M. C., Geology of Ohio - The Silurian, 1998). The thickest accumulations of salt found in Ohio are located within units B, D, E, and F, resulting from being mechanically mined underground and by nearby solution wells within the Michigan and Appalachian Basins. Although most salt beds are formed in shallow seas, these salt beds are thought be formed in relatively deep marine basins with density-layering conditions created by the salinity variations (Wickstrom, Slucher, Baranoski, & Mullett, 2008). The Salina Group ranges in thickness from approximately 235 feet to 335 feet. In western Ohio, the Salina Group is subdivided into the Greenfield Dolomite and Tymochtee Dolomite, which is equivalent to the units identified A-G in central and eastern Ohio. The Greenfield Dolomite and the Tymochtee Dolomite was deposited in shallow seas or tidal flats (Hansen M. C., Geology of Ohio - The Silurian, 1998).

Above the Saline Group is the Bass Island Dolomite, which is the youngest Silurian aged unit in the state of Ohio (Hansen M. C., Geology of Ohio - The Silurian, 1998). It is laterally extensive and can be found in Michigan, Ohio, and northwestern Pennsylvania (Wickstrom, Slucher, Baranoski, & Mullett, 2008). Some older studies have attempted to subdivide the Bass Island into smaller units, although, evidence has more recently shown that the Bass Island Dolomite cannot be differentiated in most of the Ohio-Michigan region (Janseens, 1968). The Bass Island Dolomite generally consists of thinly bedded, brown, crystalline to granular argillaceous, laminated dolomite (Norris, 1975). It is a successful local oil and gas reservoir in Erie County, Pennsylvania and in western New York. Wells drilled in eastern Ohio often contain a carbonate breccia zone, containing high permeability and porosity, utilized by several brine injection wells (Wickstrom, Slucher, Baranoski, & Mullett, 2008).

Overlying the Bass Island Dolomite, in ascending order, is the Helderburg Limestone, Oriskany Sandstone, Bois Blanc Formation, and the Onondaga Limestone (Figure 2-3). The Helderburg Limestone generally consists of carbonates with interbedded siliciclastics and chert (Lewis, McDowell, Avary, & Carter, 2009), specifically, dense limestone with about 5-20% finely porous shale and traces of fine-grained sands (Dow, 1962). Data collected in Shadyside, Ohio suggest the presence of only secondary porosity, and that if permeability exists, it occurs only along faults or within fractures. The Helderburg Limestone consists of subtidal, intertidal and supratidal deposits representing a transgression. These sediments were deposited in an epeiric sea with shallow water depths in the center of the basin, not excending 150-200 feet. The Taconic uplift bounded the Helderburg Sea to the southeast, while also supplying the intermittent influx of clastic sediments (Lewis, McDowell, Avary, & Carter, 2009).

The Oriskany Sandstone represents a major change in deposition, emphasized in the lithology, from carbonate sedimentation to predominantly clastic deposition. The Oriskany Sandstone consists of well-sorted, white to light gray (Wickstrom, Slucher, Baranoski, & Mullett, 2008), medium grained quartzose sandstone, loosely cemented, and fossiliferous. The upper and lower contacts of this formation appear to be sharp (Dow, 1962), with porosity and permeability varying greatly throughout. Porosity ranges from approximately less than 5% within the limestones to up to more than 20% where second porosity has occurred. The permeability ranges from approximately 0.1 to almost 30 md. This formation has been used in waste disposal and natural gas storage in various locations across the basin (Wickstrom, Slucher, Baranoski, & Mullett, 2008).

Onondaga Limestone unconformably overlies the Oriskany Sandstone in southern Ohio (Gupta, 2008). In other parts of the state, the equivalent Bois Blanc Formation, Columbus Limestone, and Delaware Limestone is found (Figure 2-3). The rocks of the Bois Blanc Formation found in Ohio were once referred to as the Onondaga Limestone (Dow, 1962).

OLENTANGY SHALE

Several alternating units of sandstone and limestone cover the Onodaga Limestone, which encompass the Upper and Lower Olentangy (Gupta, 2008). The Lower Olentangy is described in central Ohio as medium to dark gray shale containing fine-grained, continuous, lenticular and concretionary limestone beds, with minor amounts of pyrite and marcasite found within the unit (Tillman, 1970). The Upper Olentangy is described in central Ohio as dark green gray shale containing brownish-black carbonaceaous, pyritiferous shale that appear to be continuous (Tillman, 1970). The interbedded shales indicate fluctuating oxygen conditions during deposition and bottom waters of the western margin of the Appalachian Basin (Over & Rhodes, 2000).

OHIO SHALE

The Ohio Shale is generally described as a fissile, dark gray-black, organic-rich shale with small amounts of siltstone and sandstone (Alshahrani & Evans, 2014). The Ohio Shale is often subdivided into two members, in ascending order, the Huron Member and the Cleveland Member (Roen, 1984; Alshahrani & Evans, 2014). The Huron and Cleveland Members are black, organic-rich shales. The Huron Member is known for large carbonate concretions that formed around fish fossils (Alshahrani & Evans, 2014). The Huron Member forms a ledge over the less resistant Olentangy Shales in overlies (Over & Rhodes, 2000). The Cleveland Member is exposed along Lake Erie Ohio, reaching its maximum thickness of approximately 100 feet in north central Ohio (Roen, 1984). These members are generally divided by the green-gray siltstone and shales of the Chagrin Shale, or the equivalent Three Lick Bed (Roen, 1984; Alshahrani & Evans, 2014). This unit generally thickens to the east to 400 feet thick in northern Ohio. This unit is known for small ironstone concretions around crustacean, brachiopods, bivalve, cephalopod, conulariid, crinoid, and fish fossils (Alshahrani & Evans, 2014).

BEDFORD SHALE AND BEREA SADNSTONE

The lower contact of the Bedford Shale is marked by a thin pyritic bed layer that contains brachiopods, conodonts, fish plates and shark fragments. The Bedford Shale generally consists of blue-gray shales and siltstones eastward to the Ohio-Pennsylvania line. A distinct red shale is prominent in the Bedford Shale towards the West, outcropping in Lorain and Cuyahoga Counties, Ohio. In Lorain County, a max thickness of 150 feet of Bedford Shale is found. The upper contact of the Bedford Shale is a disconformity, representing an erosional period before the deposition of the Berea Sandstone (Banks & Feldman, 1970).

The Berea Sandstone consist of predominately sandstone that is resistant to weathering and erosion, effectively shaping the topography of northeastern Ohio, forming massive cliffs, extensive terraces and escarpments, gorges, rapids, and plunge pools (Banks & Feldman, 1970).

The Bedford Shale and the Berea Sandstone sediments derive from a northern source, thought to be eastern Canada, deposited as a delta fan across central and eastern Ohio. These formations represent a cycle of deposition during an oscillation of the land and sea between two periods of quiescence (Pepper, De Witt Jr., & Demarest, 1954).

SURFACE GEOLOGY

The surface geology found across Ohio ranges from sediments dating from the Ordovician to Permian. In general, the Ordovician sediments are found in western Ohio, and younger sediments trend to the east to the Permian sediments. The Ordovician sediments are concentrated in the southwestern part of Ohio, while Devonian and Mississippian sediments are found in the northwest corner of Ohio. Near Lorain County, Ohio, Mississippian surface sediments are generally found in outcrop (Figure 2-2).

2.1.2 REGIONAL CROSS SECTIONS

Two regionally published cross sections are provided. Figure 2-7 is a regional west-northeast cross section extends from eastern Erie County, Ohio to Bedford County, Pennsylvania (Janssens A. , 1973) It shows the subsurface stratigraphy and structure from the surface to depth, showing the unconformity located beneath the Mt. Simon Sandstone. Figure 2-8 is a regional west-southeast cross section extending from Wood County, Ohio to Elgin County, Ohio (Ryder, et al., 2012). It shows to subsurface stratigraphy, specifically from the Knox Dolomite to the Mt. Simon Sandstone, allowing for reservoir characteristics to be seen in detail of the proposed confining and injection zone, regionally.

2.1.3 STRUCTURAL GEOLOGY

Regionally, the strata has been uplifted, tilted, and warped into low, broad folds since originally being deposited as a horizontal layer. The dip of the strata is to thesouth and southeast across Ohio (Mather, 1838; Hubbard, Stauffer, Bownoeker, Prosser, & Cumings, 1915). Some major structural features of the region are the Cincinnati and Findlay Arches and the Appalachian and Michigan Basins (Slucher, et al., 2006; Hubbard, Stauffer, Bownoeker, Prosser, & Cumings, 1915) shown on Figure 2-9 (Slucher, et al., 2006). These features influence the spatial distribution of sediments in Ohio (Slucher, et al., 2006).

The Findlay Arch formed a broad, shallow platform in northwestern Ohio, where there have been significant oil and gas production in the Ordovician age Trenton Limestone (Wickstrom, et al., 2005).

The Cincinnati Arch is an elongated anticline, found across Ohio, eastern Indiana, and central Kentucky. The primary axis extends from west of Lake Erie to Nashville, Tennessee. The oldest rocks are exposed in the center of the dome, with successively younger beds in concentric belts around the center (Hubbard, Stauffer, Bownoeker, Prosser, & Cumings, 1915). The Cincinnati Arch is a broad stable region that is uplifted compared to the strata of nearby areas. The Findlay Arch is structural feature that separates the Michigan and Appalachian Basins. On the eastern and northwestern flanks of the arches, the bedrock dips gently into the Appalachian and Michigan Basins, respectively (Figure 2-9) (Slucher, et al., 2006).

The Appalachian Basin is regionally extensive, extending from Alabama to east-central New York. Nearly continuous deposition during the Paleozoic is recorded within the sedimentary layers found within the basin. Rocks within the Ohio portion of the Appalachian Basin generally dip to the southeast towards the interior of the basin (Slucher, et al., 2006).

The Michigan Basin is a nearly circular basin that is approximately 400 kilometers (km) in diameter, laterally covering Michigan and parts of northwestern Ohio, northern Indiana, northeastern Illinois, eastern Wisconsin, and southern Canada (Swezey, 2008). Strata of the Michigan Basin predominantly consist of limestone and dolomite, although there are significant siliciclastic and evaporate components (Howell & Van Der Pluijm, 1999). The parts of the Michigan Basin preserved in northwestern Ohio is mostly covered with glacial deposits, dipping mainly towards the north-northwest, towards the center of the basin (Slucher, et al., 2006).

2.1.4 HYDROGEOLOGY

The regional hydrology is discussed below in Section 2.7.

2.2 MAPS AND CROSS SECTIONS OF THE AOR [40 CFR 146.82(A)(2), 146.82(A)(3)(I)]

This section provides maps and cross sections per 40 CFR 146.82 (a) (2) showing key features important to the permit, accompanied by a brief narrative describing the interpretation of these features.

2.2.1 LOCAL CROSS SECTIONS

Local Northeast-Southwest, West-East, and Northwest-Southeast cross sections are provided as Figures 2-10 through 2-12, respectively. The wells within the AOR do not penetrate the injection or confining zones; however, wells in the vicinity do provide enough data to correlate laterally and constrict particular data at the Lorain County Landfill, which will be verified and updated after the installation of the well, prior to the injection of CO_2.

The subsurface can be seen in various wells in the vicinity of the Lorain County Landfill, through the confining and injection zone, reaching the Precambrian Unconformity. The regional and local hydrogeology is discussed in Section 2.7.

2.2.2 LOCAL STRUCTURE AND ISOPACH MAPS OF THE INJECTION ZONE

Local structure and isopach maps of the confining zone are provided as Figures 2-13 and 2-14, respectively. The lateral extent of the Rome and Conasagua Formations, consisting of the proposed confining zone for the Lorain County Landfill, can be seen on the local cross sections. The structure map of the confining zone shows a general dip to the east southeast. Northwest of our site, the top of the Conasauga Formation can be seen at approximately 3155 feet mean sea level (MSL), deepening to the east to approximately 5,354 feet MSL (Figure 2-13). The thickness of the confining zone is observed on the cross sections and the regional isopach of the confining zone (Figure 2-14), ranging from approximately 314 feet to the northwest to approximately 657 feet to the southeast.

Local structure and isopach maps of the injection zone are provided as Figures 2-15 and 2-16, respectively. The lateral extent of the Mt. Simon Sandstone, consisting of the proposed injection zone for the Lorain County Landfill, can be seen on the local cross sections. The structure map of the injection zone shows a general dip to the east southeast. Northwest of our site, the top of the Mt. Simon Sandstone can be seen at approximately 3,493 feet MSL, deepening to the east to approximately 5,955 feet MSL (Figure 2-15). The thickness of the injection zone is observed on the cross sections and the regional isopach of the injection zone (Figure 2-16), ranging from approximately 90 feet to approximately 140 feet. The variable thickness observed on the isopach of the injection zone is thought to be attributed to its fluvial depositional environment. The fluvial environment is much like the modern-day river environment, where there are thicker sediments accumulated where water was moving slower and thinner sediments accumulated where water was moving faster.

2.3 FAULTS AND FRACTURES [40 CFR 146.82(A)(3)(II)]

Per 40 CFR 146.82 (a) (3) (ii), any faults or fractures in the area were identified and discussed. There are no observed faults within the AOR. The faults nearest to the Lorain County Landfill, from nearest to farthest towards the east, southeast direction, are the Middleburg Fault, Akron Fault, Suffield Fault, Smith Township fault, and the Highlandtown Fault (Figure 2-9). The nearest known fault to the Lorain County Landfill is approximately 17 miles to the northeast.

Due to the distance between the potential injection site and the nearest fault, the fault does not pose a threat to containment or pose a potential pathway for the injected CO_2.

2.4 INJECTION AND CONFINING ZONE DETAILS [40 CFR 146.82(A)(3)(III)]

This section provides vital information regarding the proposed confining and injection zone, including mineralogy, porosity and permeability data, and waste compatibility per 40 CFR 146.82 (a) (3) (iii).

2.4.1 PROPOSED CONFINING ZONE

The proposed confining zone associated with the Mt. Simon Sandstone is the Rome and Conasauga Formations. The Eau Claire and its equivalent Rome and Conasagua Formations are considered a primary seal regionally, consisting of siltstones, shales, and dolomitic sandstones with low permeability and porosity, making it an ideal confining zone (Medina & Rupp, 2012; Gupta, et al., 2017; Medina, Rupp, & Barnes, 2011)

The Rome Formation predominately consists of dolomite (Janssens, 1973). In eastern Ohio, directly overlying the Rome Formation, is the Conasauga Formation, consisting of shale with minor interbedded carbonate, siltstone, and sandstone. Eastward from central Ohio, the Conasauga Formation gradually transitions into a sandy dolomite. A few wells that penetrated the Conasauga in eastern Ohio, described the formation as sandy, predominantly microcrystalline to finely crystalline, light to dark gray and brown dolomite with varying amounts of interbedded sandstone (Gupta, et al., 2017).

The confining zone can be seen regionally dipping towards the east southeast with a fairly consistent thickness, only thickening slightly as you reach into the Pennsylvania counties (Figure 2-14). The local cross sections show a similar dip to the east and southeast (Figures 2-10 through 2-12). Based on the fairly consistent dip of the injection zone, the estimated depth of the injection zone at the Lorain County Landfill is approximately 3,640 feet MSL (Figure 2-16).

In central eastern Ohio, the porosity of the Rome Formation was determined from petrophysical methods, which ranged from 0-0.11%, the average porosity determined to be approximately 0.043%. The porosity of the Conasauga Formation determined from petrophysical methods ranged from 0-0.15%, the average porosity determined to be approximately 0.048% (Gupta, et al., 2017). These values were utilized in the modeling discussed in Section 3, but will be verified and updated after the installation and logging of the well is complete, but before beginning the injection of CO_2.

2.4.2 PROPOSED INJECTION ZONE

The proposed injection zone is the Mt. Simon Sandstone. The Mt. Simon Sandstone has significant potential as a reservoir for CO_2 sequestration across the Midwest. A direct relationship between thickness and storage capacity of the Mt. Simon Sandstone has been proposed (Medina & Rupp, 2012), and the Mt. Simon Sandstone is estimated to be between 100 and 200 feet thick in the vicinity of the Lorain County Landfill (Figure 2-4). Although the Mt. Simon Sandstone cannot be used in eastern Ohio as an injection zone, it is considered stable in central Ohio and had been utilized as an injection zone for decades (DNR, 2017). The injection zone can be seen regionally mimicking the orientation of the confining zone, dipping towards the southeast with a fairly consistent thickness, again only thickening slightly as you reach to the Pennsylvania counties (Figure 2-16). Figure 2-8 demonstrates the injection zone regionally towards the west, showing the thickness increasing towards the western Ohio Counties. Published literature determined that the Mt. Simon Sandstone continues to thickness across western Ohio, Illinois, and Indiana (Medina & Rupp, 2012).

The proposed injection zone formation mimics the regional dip of the confining zone, dipping towards the southeast with a fairly consistent thickness, only thickening slightly as you reach into the Pennsylvanian counties (Figure 2-8). The local cross sections show a similar dip to the east and southeast (Figures 2-10 through 2-12). Based on the fairly consistent dip of the injection zone, the estimated depth of the injection zone at the Lorain County Landfill is approximately 3980 feet MSL (Figure 2-15).

As discussed in Section 2.1.1, the well nearest to the Lorain County Landfill with available permeability and porosity data of the Mt. Simon Sandstone, found in Richland County, was evaluated in detail to estimate conditions of the Mt. Simon Sandstone locally near the site. Sensitive, Confidential, or Privileged Information [redacted]

2.4.3 PROPOSED LOWER CONFINING ZONE

The proposed lower confining zone is the Precambrian Granite. Most of the igneous rocks identified in Ohio are predominantly granite and related rocks, such as rhyolite and diorite. They typically contain various other minerals, including orthoclase, oligoclase, plagioclase, quartz, potassium feldspar, andesine, and epidote, with small amounts of biotite, hornblende, magnetite, hematite, pyrite, zircon, garnet, leuocoxene, tourmaline, apatite, hypersthene, and augite. Most of the metamorphic rocks identified in Ohio are either metamorphosed sedimentary rocks and metamorphosed basic igneous rocks. The metamorphosed sedimentary rocks generally consist of labradorite, hornblende, hypersthene, biotite, hematite, chlorite, and garnet. Another group of metamorphosed rocks include gneiss and some schist. There is considerable variation in these rocks throughout the well samples taken from Ohio. Many samples contained banded units; the lighter bands consist of orthoclase, microcline, quartz, muscovite, and biotite, and the darker bands consist of plagioclase, hornblende, biotite, and chlorite (Summerson, 1962). This Precambrian unit forms a stable, base or craton of continental plates (Mudd, Johnson, Christopher, & Ramakrishnan, 2003).

2.5 GEOMECHANICAL AND PETROPHYSICAL INFORMATION [40 CFR 146.82(A)(3)(IV)]

The geomechanical properties described in this section are derived from geologic literature for the area surrounding the Lorain County Landfill. This section begins with addressing the general mechanical properties of the rock layers to be encountered in the drilling of the well including any indication of faults, fractures, fissures, or karst features. Secondly, any available information on stress tensors, or the nature of earth stress, is discussed based on findings in geologic literature. Finally, the available geomechanical data are reviewed for the injection zone and confining zone.

When the well is drilled, these estimations will be compared to actual laboratory-derived statistics from the cores obtained in the confining zone and injection zone.

2.5.1 KARST

According to the Ohio Department of Natural Resources (ODNR) Karst Interactive Map, there are no karst features suspected or verified in Lorain County. In northern Ohio, the majority of karst features are found in Sandusky County which is approximately 30 miles west of Lorain County. The karsting features are to the west of the Lorain Carbon Zero Solutions, LLC, Lorain County Landfill and primarily in Sandusky county.

2.5.2 LOCAL CRUSTAL STRESS CONDITIONS

There are noted strike-slip conditions to the east of the Lorain County Landfill. They are approximately 20 miles to the east as to not likely affect crustal stress conditions (ODNR, 2018). As such, the strike-slip stress regime is not having an affect on the stress and it would be valid to assume a normal stress regime for the confinement zone and injection zone. These findings will be verified with the geophysical well logs and laboratory analysis of borehole cores recovered during the drilling of the well.

2.5.3 DETERMINATION OF VERTICAL STRESS S_V FROM DENSITY MEASUREMENTS

The magnitude of the vertical stress (S_v) can be represented by the overburden (lithostatic pressure) and can be calculated by integrating wireline log-derived rock densities at the depth of interest. [redacted]

Unit	MPa	Psi
Top of Rome confining zone	Sensitive, Confidential, or Privileged Information [redacted]	

Top of Mt. Simon Sandstone injection zone	Sensitive, Confidential, or Privileged Information [redacted]

2.5.4 MAXIMUM AND MINIMUM HORIZONTAL STRESS AZIMUTH

In vertical wells, breakout or tensile fractures usually indicates that S_{hmin} is the minimum principal stress and the posibiilty of large differences between the two horizontal stress S_{hmax} and S_{hmin} exists. Local published geologic data is currently unavailabe to determine the minimum and maximum horizontal stresses.

When borehole image logs are gathered during drilling, these will be analyzed to determine the horizontal stresses and compare this data to the vertical stress. Once this determination is made, it can be compared to the relationship between principal stresses and fault types which follows the guidance below (Zoback, 2007).

	Stress		
Regime	**S1**	**S2**	**S3**
Normal	S_v	S_{hmax}	S_{hmin}
Strike-Slip	S_{hmax}	S_v	S_{hmin}
Reverse	S_{hmax}	S_{hmin}	S_v

2.5.5 ELASTIC MODULI AND FRACTURE GRADIENT

The elastic moduli (or constants) include Poisson's ratio, bulk modulus, shear modulus, and Young's modulus. These values characterize the properties of a rock that define how the rock deforms during applied stress and how the rock recovers when stress is released.

Fracture pressure (also known as breakdown pressure) is the pressure above which fluid injection will cause a formation to fracture hydraulically (brittle failure). Fracture gradient is the pressure increase per unit depth.

The estimate for fracture gradient for the Mt. Simon Sandstone in this area is 0.65 psi/foot. The Environmental Protection Agency (EPA) requires using 90% of the fracture gradient for maximum injection pressure. As such, a maximum pressure gradient of 0.59 psi/foot was used in the reservoir model (EPA, 2018).

The elastic moduli parameters were derived from reviewing Class VI permit applications in the regional area and reviewing geologic literature (references can be found in Appendix 3-1). Actual elastic moduli data will be derived from cores taken in the Confining Zone and Injection Interval during drilling.

2.5.6 INJECTION ZONE FRACTURE PRESSURE

The Injection Zone fracture gradient was suggested to be 0.65 psi/foot from reviewing Class VI permit applications in the regional area and reviewing geologic literature (references can be found in Appendix 3-1).

When the well is drilled, fracture gradient data will be collected from conducting step-rate injection tests.

2.5.7 CONFINING ZONE FRACTURE PRESSURE

The confining zone fracture gradient was suggested to be 0.65 psi/foot from reviewing Class VI permit applications in the regional area and reviewing geologic literature (references can be found in Appendix 3-1).

2.6 SEISMIC HISTORY [40 CFR 146.82(A)(3)(V)]

A review of historical seismic activity through January 2021, encompassing the entire state of Ohio, was obtained from the United States Geological Survey's (USGS) online National Earthquake Information Center (NEIC). Earthquakes with epicenters within the area investigated had known or estimated magnitudes up to 5.4. Available data are presented on Table 2-1.

In Ohio, most of the seismic activity is concentrated in the west, northeastern, and southern edge of the state (Figure 2-17). Central Ohio is an area that has been historically low in earthquakes and seismic activity, as shown on the seismic risk map (Figure 2-17). Only very small ground motion and minimal damage occur when infrequent earthquakes occur.

A total of 140 seismic events were reported through the USGS. The closest recent reported event occurred on January 20, 2014 (2.1 magnitude), with an epicenter located more than 10 miles east of the site, near North Olmsted, Ohio (Figure 2-18). The most recent event occurred on January 22, 2021 (2.4 magnitude) with an epicenter 0.5 km (0.31 miles) northwest of Fort Shawnee, Ohio, approximately 185 km (115 miles) southwest of the site. The most severe event recorded in Ohio since 1900, occurred on March 9, 1937 (5.4 magnitude), with an epicenter located 209 km (130 miles) southwest of the site, near New Bremen, Ohio.

In the last 10 years, there has been discussion regarding active injection wells and how they might influence seismic events. The sequence of events that led to this discussion occurred in Mahoning County, Ohio, approximately 145 km (90 miles) from Lorain County.

The first Class II saltwater disposal well permitted in Mahoning County Ohio was in 1985, followed by eight additional Class II wells drilled between 1985 and 2004. The dominant waste disposed in these Class II wells was production brine associated with conventional oil and gas operations. Once the unconventional shale plays gained interest, additional disposal was requested, thus five commercial disposal wells were drilled - Northstar 1 through 4 and 6 (EPA, 2014).

A series of 12 small seismic events were recorded in Mahoning County starting on March 17, 2011, culminating in a recorded M4.0 event on December 31, 2011 (EPA, 2014). After evaluation of scientific evidence and the data collected, Ohio Department of Natural Resources (ODNR) concluded that two Class II disposal well operations were linked to the seismic activity recorded in Ohio. The largest event in Mahoning County was linked to Northstar 1. The Division of Oil and Gas Resources Management (DOGRM), a department within the ODNR, issued cease injection orders for both these wells (GPC, 2017).

ODNR suggested that pressure associated with the disposal activities interacted with an undetected, Precambrian fault near Northstar 1. Drilling of Class II injection wells are now prohibited to drill into Precambrian basement rock (EPA, 2014). In 2012, more extensive monitoring of existing injections wells was implemented as well as additional testing and permitting requirements for new injection well applications. This allows DOGRM to order specific tests such as pressure fall off tests, spinner tests, tracer tests, step rate tests, and any other deemed necessary.

2.7 HYDROLOGIC AND HYDROGEOLOGIC INFORMATION [40 CFR 146.82(A)(3)(VI), 146.82(A)(5)]

2.7.1 REGIONAL HYDROGEOLOGY

Average precipitation across the state of Ohio ranges between 30 to 44 inches a year (increasing from northwest to southeast). Infiltration from the precipitation recharges the aquifers, attributing to the abundant surface and groundwater resources it obtains. The aquifers in Ohio can be divided into three major types, sand and gravel aquifers, interbedded sandstone/shale, and carbonate aquifers. These major classifications are illustrated on Figure 2-19 and discussed below in more detail (EPA, 2014).

SAND AND GRAVEL AQUIFER

The sand and gravel aquifers are found in valleys cut into the bedrock by pre-glacial and glacial streams which were backfilled with the sand and gravel deposits, located throughout the state near the Ohio River, its major tributaries, and other stream channels. The production of the coarser sand and gravel deposits can be the most productive water bearing formation, yielding up to 500 to 1,000 gallons per minute (gpm), although lower yield are more common (EPA, 2014).

SANDSTONE AQUIFER

Interbedded Mississippian and Pennsylvanian age sandstone and shale aquifers are the dominate bedrock aquifer in eastern Ohio, containing variable thickness and aerial extent, dipping a few degrees to the southeast. These aquifers generally yield water production of approximately 25 gpm, but can reach up to 50 to 100 gpm in the thicker sandstone units toward the southeast, located closer to the Application Basin. The more productive stratigraphic units include (1) Pennsylvanian Sharon through Massillon Formations, and the Homewood Sandstone within the Pottsville and Allegheny Groups and (2) Mississippian Berea Sandstone, Cuyahoga Group, Logan and Blackhand Formations (EPA, 2014).

CARBONATE AQUIFER

The dominant carbonate aquifer in western Ohio consists of Silurian and Middle Devonian limestone and dolomite. These aquifers can yield from 100 to over 500 gpm of water production due to fractures and dissolution features, which increase its permeability. The most productive stratigraphic units include the Lockport Dolomite and equivalent units (EPA, 2014).

2.7.2 DEFINING THE UNDERGROUND SOURCE OF DRINKING WATER (USDW)

The Lockport Dolomite was once considered within the USDW in a study done in northwestern Ohio in 1970. The USDW was re-evaluated in eastern Ohio in 1982, producing a contour map that delineated the deepest fresh-salt water interface defined using the EPAs definition of a USDW "of 10,000 mg/l of total dissolved solids". In 2011, the Ohio Geological Survey combined the earlier maps to create a new map statewide USDW map (Riley, Wicks, & Perry, 2010) (Figure 2-20). The base of the lowermost USDW at the Lorain County Landfill and the surrounding area is estimated between 750 and 800 feet MSL.

The aquifer used to define the base of the USDW in Lorain County, Ohio is found within the Consolidated Bedrock of the Berea Sandstone, which is characterized as a sandstone aquifer (EPA, 2014).

The Berea Sandstone is Mississippian age (Section 2.1.1), and typically yields 3-10 gpm, assuming long-tern withdrawal. Unconsolidated aquifers consisting of sand and gravel lenses in glacial till also contribute to ground water production in domestic wells, more common in western and southwestern Lorain County Ohio. The yields are often consistent compared to the consolidated bedrock aquifers in the county (Barber, 1989).

In areas of Lorain County where neither the Berea Sandstone or the sand and gravel lenses were present, groundwater supplies had to be developed from shale aquifers, which often yielding less than 3 gpm (Barber, 1989).

GROUNDWATER FLOW

Potentiometric surface maps, which contour the groundwater surface, in the Lake Erie Watershed allow for the determination of the direction of groundwater flow. Groundwater in general flows from higher elevations to lower elevations perpendicular to the contour line orientations. The groundwater flow in Lorain County, within the consolidated bedrock aquifer, can be seen dipping slightly to the north (ODNR, 2019) (Figure 2-21).

GEOCHEMICAL CHARACTERIZATION OF USDW

The EPA investigated the major ion composition within each major aquifer type in an Ohio Ground Water Quality Report 305 (b) (2000). Bicarbonate, calcium, magnesium, sulfate, sodium and potassium, and chloride ion concentrations were evaluated. The sandstone aquifers in general, had the highest concentration of sodium and chloride, while the carbonate aquifers had the highest concentration of bicarbonate, calcium, magnesium, and sulfate. The total dissolved solids (TDS) is also observed lower in the sandstone aquifers, attributed to the higher silica sand and lower carbonate rock content in the sandstones (Ohio EPA, 2000).

2.8 GEOCHEMISTRY [40 CFR 146.82(A)(6)]

The size, shape, distribution, and connectivity of the pore spaces within the Mt. Simon Sandstone dictate how the fluids will migrate and react with accessible solids within the formation; these properties are linked to the variable porosity and permeability that formation exhibits through the injection and post injection phase of CO_2 storage (Swift, et al., 2014). During the initial injection of the supercritical CO_2 into deep geologic formations, the sequestration primarily relies on the impermeabile confining layer as the trapping mechanism (Kelemen, Benson, Pilorge, Psarras, & Wilcox, 2019) as the supercritical CO_2 plume migrates slowly (hydrodynamic) (Liu, Lu, Zhu, & Xiao, 2011). There are three secondary trapping mechanisms that could aid in the CO_2 storage ability, these include:

1. Solubility trapping caused by dissolution of the CO_2 into aqueous pore fluid (Kelemen, Benson, Pilorge, Psarras, & Wilcox, 2019). The regional groundwater flow is insignificant during in injection of the supercritical CO_2, but plays an important role in the plume migration after injection ceases. The contuial flow of groundwater aids in the spread of the CO_2 plume, as well as boosts geochemical reactions. The geochemical dissolution of the significant amount of K-feldspar in the Mt. Simon Sandstone leads to a substantial increase in porosity throughout the zone. This increased solubility and mineral trapping makes the Mt. Simon Sandstone ideal for long-term CO_2 storage in the Midwest (Liu, Lu, Zhu, & Xiao, 2011).
2. Residual trapping caused by capillary forces (Kelemen, Benson, Pilorge, Psarras, & Wilcox, 2019). During the 100 year modeled injection, the flow of the supercritical CO_2 is constrained by the flow dynamics and capillary pressure from the intrusion of the CO_2. After injection ceases, the capillary pressure of the formation and the density contrast between the CO_2 and the original brine drive the CO_2 into pore space until they reach equilibrium (Liu, Lu, Zhu, & Xiao, 2011).

3. Mineral trapping caused by chemical interactions between CO_2, pore fluid, and rock (Kelemen, Benson, Pilorge, Psarras, & Wilcox, 2019). During the modeled 100 year period, the major chemical reactions observed in the Midwest during injection of CO_2 into the Mt. Simon Sandstone, are dolomite dissolution and calcite, magnesite, and ankerite precipitation. These carbonate reactions increases the porosity by approximately 1%, and decreases the pH to approximately 3. After the injection period, the CO_2 continues to be dissolved into the brine, which results in continued lower pH levels, and the dissolution of nearly all the K-feldspar near the wellbore, being replaced by alunite and anhydrite near the wellbore and other secondary clay minerals farther from the wellbore. This ability for the siliciclastic sandstone to breakdown the alumino-silicate minerals and precipitate these secondary minerals lead to good trapping potential in the Mt. Simon Sandstone across the Midwest (Liu, Lu, Zhu, & Xiao, 2011).

The extent of these secondary trapping mechanisms is site specific (Kelemen, Benson, Pilorge, Psarras, & Wilcox, 2019). Across the Midwest, the CO_2 injected into the Mt. Simon Sandstone, is largely controlled by hydrodynamic and solubility trapping. With time, the hydrodynamic trapping decreases as the supercritical CO_2 dissolution occurs into the brine, which results in the increase in solubility trapping. Mineral trapping is also expected to increase over time (Liu, Lu, Zhu, & Xiao, 2011).

2.9 SITE SUITABILITY [40 CFR 146.83]

The summary below is a description of how the proposed injection site meets the suitability requirements set forth at 40 CFR 146.83. This demonstration exercises and synthesize that the injection zone can accommodate the total anticipated CO_2 volume and that the confining zone has sufficient integrity to contain the proposed injected volume and any displaced fluids in the site characterization data described above.

Lithological facies exert control on porosity, permeability, and mineralogy. Therefore, a good facies analysis and assessment on subsurface distribution aids in anticipating heterogeneity in these properties and the associated effects on the injection and storage capabilities of the site. For this permit, the regional stratigraphy is discussed. A generalized geologic stratigraphic column of Ohio is provided in Figure 2-3. The relevant formations are discussed in detail from surface to depth in Section 2.1.1, as well as briefly summarized below.

The known Precambrian history of Ohio began approximately 1.4 to 1.5 billion years ago, during the emplacement of a 7-mile thick layered sheet of granite and rhyolite. These predominately crystalline igneous and metamorphic rocks are buried deeply beneath the subsurface at depths ranging from approximately 2,500 feet in western Ohio to approximately 13,000 feet in southeastern Ohio (Hansen M. C., 1997).

The basal Cambrian rock unit beneath most of Ohio, which directly overlies the Precambrian unit, is the Mt. Simon Sandstone, which consists of fine-grained to conglomerate sandstone, often poorly consolidated, with few areas containing siliceous cement. Locally, the Mt. Simon Sandstone is estimated to be between 100 and 200 feet thick around the Lorain County Landfill (Figure 2-4) (Janssens, 1973). The Mt. Simon Sandstone is overlain by the Eau Claire Formation in western Ohio and by the Rome Formation and Conasauga Formation, in ascending order, in eastern Ohio (Figure 2-3) (Janssens A. , 1973). The Eau Claire Formation is composed of a low porosity crystalline dolomite, sandy dolomite, dolomitic and feldspathic sandstone, siltstone and shale (Wickstrom, et al., 2005). The Rome formation predominately consists of dolomite (Janssens, 1973) and considered impermeable, excluding the various interbedded sand intervals (Wickstrom & Baranoski, 1993), and estimated to be approximately 300 feet thick locally around the Lorain County Landfill (Janssens, 1973). In eastern Ohio, directly overlying the Rome Formation, is the Conasauga Formation, consisting of shale with minor interbedded carbonate, siltstone, and sandstone. Eastward from central Ohio, the Conasauga Formation gradually transitions into a sandy dolomite (Gupta, et al., 2017). The Conasauga Formation is estimated to be approximately 50 feet thick locally around the Lorain County Landfill (Janssens, 1973). The Kerbel Formation overlies parts of the Eau Claire Formation and the Conasauga Formation in central Ohio, which consists of upward-coarsening dolomitic sandstone, estimated to be approximately 50 feet locally around the Lorain County Landfill (Appendix 2-2) (Janssens, 1973). The Knox Dolomite is laterally extensive across Ohio, covering the Eau Claire Formation in western Ohio, the Kerbel Formation in central Ohio, and the Conasauga Formation in eastern Ohio (Figure 2-3). The Knox Dolomite is often considered part of the Trempealeau, which is dolomitized limestone found throughout most of Ohio, marked by the Knox Unconformity (Cramer, 1990). This unconformity is interpreted as the base unit of the Ordovician in Ohio (Hansen M. , 1997). The Knox Unconformity, in places, represent a hiatus of non-deposition and/or erosion of approximately 30 to 40 million years (Brett & Algeo, 1999).

After the erosion that created the Knox Unconformity, the Lower Ordovician Wells Creek Formation was deposited, which consists of shale, dolomite, and often basal sandstone (Ryder, Harris, & Repetski, 1992), averaging approximately 20 feet regionally (Wickstrom, Gray, & Stieglitz, 1992; Hansen M. C., The Geology of Ohio - The Ordovician, 1997). Regarding petroleum geology, the Wells Creek Formation acts as a seal rock for hydrocarbon reservoirs of the Knox Group (Wickstrom, et al., 2005). The contact between the Wells Creek Formation and the overlying Black River Group is generally sharp and well defined. The lithology changes from the shales and argillaceous (dirty) carbonates to clean limestone and dolomite (Wickstrom, Gray, & Stieglitz, 1992). The Black River Group consists of uniform lithology across the region (Patchen, et al., 2005), primarily fine-grained tan and gray limestone (Hansen M. C., The Geology of Ohio - The Ordovician, 1997), often micritic and pelletal, with some dolomitic and argillaceous zones (Wolfe, 2008). The diachronous contact of the Black River Group and the overlying Trenton Limestone is a gradual, interlayered zone that is approximately 10 feet thick (Patchen, et al., 2005). In general, the Trenton Limestone consists of an abundance of whole or fragmented fossils within a fine to coarse grained, gray to brown limestone. There are three distinct depositional environments of the Trenton Limestone throughout Ohio, which are platform, platform margin, and open shelf (Wickstrom, Gray, & Stieglitz, 1992). Deposited above the Trenton Limestone is the Cincinnatian Group (Ausich, 1999), which are exposed in parts of Ohio, Indiana, and Kentucky (Brame & Stigall, 2014; Smrecak & Brett, 2014), consisting of terrigenous sediments (Dattilo, Brett, Tsujta, & Fairhurst, 2008). The Cincinnatian Group was named for its rich, fossiliferous beds, containing bryozoans, brachiopods, trilobites, echinoderms, crinoids, asteroids, cyclocystoids, edioasteroids, rhombiferans, and stylophornas (Ausich, 1999). The Queenston Shale was deposited above the Cincinnatian Group and is locally referred to as the "Medina" (Jansssens A. , 1977), and often described as a distinct red shale (Brett & Algeo, 1999; Janseens, 1968). The top of the Upper Ordovician Cincinnatian Group and Queenston Shale in some parts of the state, is bounded by an unconformity known as the Cherokee Unconformity. The Cherokee Unconformity represents a hiatus of non-deposition and or erosion of approximately 3 to 4 million years (Brett & Algeo, 1999).

The Clinton Formation marks the beginning of the Silurian Period (Hansen M. C., Geology of Ohio - The Silurian, 1998), which generally consists of medium-fine grained, quartzose interbedded sandstone, siltstones, and shales, with small amounts of carbonates (Wickstrom, Slucher, Baranoski, & Mullett, 2008; Riley, Wicks, & Perry, 2010). The top of the Clinton Formation is marked by another regional unconformity identified by the "Packer Shell" at the base of the Dayton Formation (Riley, Wicks, & Perry, 2010). The Clinton Group includes the Dayton Limestone and the Rochester Shale (Figure 2-3). The Dayton Formation consists of coarsely crystalline, medium bedded dolomite (Casey, 1996), light-yellowish-gray to light-yellowish-brown, and slightly glauconitic (Janseens, 1968). The Rochester Shale consists of soft calcareous clay shale (Casey, 1996), often gray, greenish-gray, green, dark-brown, and dolomitic (Janseens, 1968), with then layers of dolomite (Casey, 1996), often light-medium greenish-gray to brownish-gray dolomite (Janseens, 1968). The thick carbonates above the Clinton-Medina Sandstones are locally referred to as the "Big Lime" (Wickstrom, Slucher, Baranoski, & Mullett, 2008). The informal grouping includes in ascending order, the Lockport Group, Salina Group, Bass Island Formation, Helderberg Limestone, Oriskany Sandstone, Bois Blanc Formation, and the Onodaga Limestone (Figure 2-3).

Several alternating units of sandstone and limestone cover the Big Lime, which encompass the Upper and Lower Olentangy (Gupta, 2008). The Lower Olentangy is described in central Ohio as medium to dark gray shale containing fine-grained, continuous, lenticular and concretionary limestone beds, with minor amounts of pyrite and marcasite found within the unit (Tillman, 1970). The Upper Olentangy is described in central Ohio as dark green gray shale containing brownish-black carbonaceaous, pyritiferous shale that appear to be continuous (Tillman, 1970). Deposited above the Olentangy is the Ohio Shale, which is generally described as a fissile, dark gray-black, organic-rich shale with small amounts of siltstone and sandstone (Alshahrani & Evans, 2014). Above the Ohio Shale is the Bedford Shale and the Berea Sandstone. The Bedford Shale generally consists of blue-gray shales and siltstones eastward to the Ohio-Pennsylvania line (Banks & Feldman, 1970). The Berea Sandstone consist of predominately sandstone that is resistant to weathering and erosion (Pepper, De Witt Jr., & Demarest, 1954). The surface geology found across Ohio ranges from sediments dating from the Ordovician to Permian (Figure 2-2).

Information on facies changes provides an understanding of how the CO_2 plume will move in the subsurface. Some of the implications of CO_2 plume migration includes leakage from the effects of an encounter with geomechanical structures, especially faults, and leakage from buoyancy forces where a porous media is filled from water moving back into the pore space (United States Environmental Protection Agency (EPA), 2013).

As CO_2 is injected in the geologic formation, the gas saturation begins to increase. Once the CO_2 injection stops, the injected CO_2 continues to migrate in response to buoyancy and regional groundwater flow. Gas continues to displace water in a drainage process at the edge of the CO_2 plume resulting in an increase of gas saturation, while at the trailing edge water displaces gas in an imbibition process resulting in an increase in water saturations. This presence of an inhibition path of saturation leads to halt at the pore scale and, subsequently, trapping of the gas phase. A trail of residual, immobile CO_2 is then left behind and the plume migrates along the top of the formation (Juanes, Spiteri, & Orr Jr., 2006); (United States Environmental Protection Agency (EPA), 2013). CO_2 is injected at a high flow rate, displacing the brine to its irreducible saturation. Due to buoyancy, the injected CO_2 forms a gravity tongue (Juanes, MacMinn, & Szulczewski, 2009).

CO_2 stream compatibility with the well and subsurface formations is important to the long-term viability of the injection operation. Formation testing with the materials used to construct the well and fluids in the injection zone and minerals in both the injection and the confining zone can demonstrate compatibility of the carbon dioxide stream. Subsurface interaction among the injectate, fluids, and solids can lead to precipitation or dissolution of minerals such that permeability, porosity, and injectivity may change. Geochemical changes due to the introduction of large amounts of carbon dioxide into the subsurface might cause trace elements such as lead or arsenic to be liberated from subsurface solids. If interactions among the fluid, CO_2, and cement might cause deterioration of the cement such that the cement sheath would become a conduit for fluid migration (United States Environmental Protection Agency (EPA), 2013).

Reactions between the cement, formation fluids, and CO_2 will not lead to deterioration in the strength of the cement sheath or increases in the porosity and permeability that could result in the cement sheath becoming a conduit for CO_2 or CO_2-rich fluids. The proposed cement sheath for their injection well will maintain integrity during the course of the project, including after injection ceases (United States Environmental Protection Agency (EPA), 2013).

Fluid chemistry also controls the amount of CO_2 that can dissolve in the fluid, affecting estimates of carbon dioxide trapping mechanisms and storage capacity. The storage capacity of the injection zone is determined by actual site-specific information such as thickness, porosity, permeability variability, and geochemistry to prove that there is sufficient capacity at the site to receive the amount of CO_2 anticipated to be injected.

There are no potential concerns regarding the confining zone integrity. An assessment of confining zone integrity involves several types of information and data gathered through the site characterization process (United States Environmental Protection Agency (EPA), 2013). The following types of information and data used to demonstrate confining zone integrity include:

— Lithological and stratigraphic data on the depth, thickness, and mineralogy of the confining zone (see Sections 2.1.1 and 2.4).
— Structural information and data on faults and fractures, including depth of origin and termination and the amount of displacement along the fault, including determinations of whether slip is consistent or variable along the fault and were such variations occur (see Section 2.3).
— Geophysical survey data including seismic, gravity, magnetic, or other geophysical methods (see Section 2.6).

To ensure protection of the USDW, a secondary confinement is recommended if the initial proposed confining zone lacks integrity to contain the proposed injected volume and any displaced fluids. Additional confining units above the proposed confining zone, the Rome and Conasauga Formations, include the Kerbel Formation, the Wells Creek Formation, and the Big Lime. The Big Lime was deposited on top of the Clinton Group and is laterally continuous across the region. Although these Formations provide a blanket security regionally for the confinement of CO_2, this unit is not necessary to ensure the protection of the USDW. Confinement is discussed further in detail in Section 2.4.

3 AOR AND CORRECTIVE ACTION

The Area of Review (AOR), as defined by the EPA 40 CFR 146.84, reads: *The area of review is the region surrounding the geologic sequestration project where USDWs may be endangered by the injection activity.*

The following sections discuss the modeling process and results, the delineation of the AOR, a tabulation of wells within the AOR, and any corrective action, if needed.

3.1 MODELING

The modeling process will involve an iterative simulation process to define the AOR. The process includes development of a conceptual model, an initial coarse grid numerical multiphase flow model, then a high-resolution simulation based on reasonable input parameters. An initial coarse grid model will be run with reasonable median input parameters. This model will be used to develop a preliminary area of review. A high-resolution simulation of the target injection zone will be run using available site-specific geologic data. A thorough sensitivity analysis will be conducted to determine the sensitivity of the AOR extent to input parameter sets and predicted input parameter ranges. Model results will include the mass of CO_2 injected, injection pressure versus time, and plumes of CO_2-rich phase saturation. The final predrilling AOR delineation will be based on simulated predictions of the extent of the maximum separate-phase plume and pressure front (whichever is greater). After the site characterization well and tests are complete, the model parameters and results will be updated based on the site-specific data.

The modeling results and analysis is presented in Appendix 3-1.

3.2 AOR AND CORRECTIVE ACTION PLAN

The modeled area of review for the proposed Class VI Injection Well at the Lorain County Landfill is determined to be 3.9-miles, which includes the area of the expected CO_2 plume. A 0.5-mile buffer was added to this area of review, making the final AOR to be evaluated for the purposes of this permit application. A radius of 4.4-miles around the proposed latitude and longitude coordinates were used for the AOR evaluation of artificial penetrations (APs).

3.2.1 ARTIFICIAL PENETRATION TABULATION AND WELL RECORDS

A potential pathway for the migration of CO_2 are through APs (freshwater and non-freshwater wells) and natural faults that penetrate the injection interval or the injection zone. The potential for APs to provide pathways are investigated in more detail in the sections below, as well as any corrective action, if needed.

A tabulation of reviewed data including non-freshwater artificial penetrations within 4.4-miles of the proposed injection well at the Lorain County Landfill is provided in Table 3-1. Well records available from the ODNR are provided in the Class VI UIC Area of Review and Corrective Action. The ODNR was established in 1965, any records associated with wells drilled and plugged prior to inception may or may not have been located. Reviewed responsive records regarding these wells have been provided in the Class VI UIC Area of Review and Corrective Action. Wells in Table 3-1 are identified with map identification numbers (Map ID Nos.) keyed to Figure 3-1.

Schematics of the non-freshwater APs within the AOR are included in the Class VI UIC Area of Review and Corrective Action.

3.2.2 CONDITION OF ARTIFICIAL PENETRATIONS WITHIN THE AOR

A total of 198 APs were identified within the AOR. Each well was evaluated to determine if it will allow movement of CO_2 (considering the properties of CO_2 within the variable phases) into or between USDWs. The 198 APs have known depths that do not penetrate the confining or injection zones, were never drilled, or are orphan domestic wells assumed to be very shallow as to not penetrate the confining or injection zones, thus poses no potential pathway for fluid migration from the injection zone that may endanger the USDW.

3.2.3 WATER WELLS AROUND THE LORAIN COUNTY LANDFILL

Water wells are listed in Table 3-2. Water wells in Table 3-2 are identified with Map ID Nos. keyed to Figure 3-2. A topographic map depicting water wells within the AOR of the Lorain County Landfill is provided as Figure 3-2. Surface bodies of water and other pertinent surface features are included in accordance with 40 CFR 146.82 (a) (2).

3.3 CORRECTIVE ACTION PLAN

The 198 APs located within the AOR do not penetrate the confining or injection zones, thus pose no potential pathway for fluid migration from the injection zone that may endanger the USDW.

4 FINANCIAL RESPONSIBILITY

Lorain Carbon Zero Solutions, LLC is providing financial responsibility for preforming corrective action, injection well plugging, PISC, site closure, and emergency and remedial response, per 40 CFR 146.85. The cost associated with each of the above activities are outlined and submitted, per 40 CFR 146.85 (a) (2) in the Class VI UIC Financial Responsibility Demonstration. The financial endorsement documentation is also provided in the Class VI UIC Financial Responsibility Demonstration.

5 INJECTION WELL CONSTRUCTION

5.1 PROPOSED STIMULATION PROGRAM [40 CFR 146.82(A)(9)]

The need for stimulation to enhance the injectivity potential of the Mt. Simon Sandstone is not anticipated. The need for stimulation will be determined once the characterization data from geophysical logs, core testing, and hydrogeologic testing is reviewed and analyzed. If it is determined that stimulation techniques are necessary, a stimulation plan will be developed and submitted to EPA Region 5 for review and approval prior to conducting any stimulation.

5.2 CONSTRUCTION PROCEDURES [40 CFR 146.82(A)(12)]

5.2.1 OPERATING DATA

This section describes the source of the CO_2 that will be delivered to the storage site, its chemical and physical properties, flow rate, and the anticipated pressure and temperature of the CO_2 at the pipeline outlet to the wellhead.

SOURCE OF CO_2

The source of the CO_2 will come from the landfill waste and waste processes. The CO_2 will be captured and run through a CO_2 purification and compression unit before entering the pipeline outlet to the wellhead. The Lorain County Landfill will be designed to capture landfill gas which is composed of methane, CO_2 and other gases. The landfill gas processing plant processes the landfill gas and the CO_2 is a residual of this process. The landfill will inject approximately 120,000 MT of CO_2 per year, or 1.4 MMT of CO_2 over the life of the well and supply it for geological storage in the Mt. Simon Sandstone.

CHEMICAL AND PHYSICAL CHARACTERISTICS OF THE CO_2 STREAM

The planned minimum acceptance specifications for the chemical composition of the CO_2 to the pipeline is shown in Table 5.1.

DAILY RATE AND VOLUME AND/OR MASS AND TOTAL ANTICIPATED VOLUME AND/OR MASS OF THE CO_2 VOLUME

The design basis for the capture facility is 85% availability (310.25 days/yr). Therefore, the daily CO_2 flow rate when the system is operational will be 387 MT/day (120,000 MT injected over 310.25 days. A total of 1.44 MMT of CO_2 will be injected at the Lorain Landfill CO_2 storage site (12 yr x 120,000 MT/yr).

PRESSURE AND TEMPERATURE OF CO_2 DELIVERED TO THE STORAGE SITE

The CO_2 will be transferred on a 10-inch diameter pipeline to the wellhead. Based on design calculations, the anticipated CO_2 pressure at the pipeline outlet (i.e., at the wellhead) will be 2500 psi. This assumes an inlet pressure of 2500 psi and an inlet temperature of 90 °F. CO_2 temperature at the pipeline outlet was calculated assuming winter soil temperature (65°F). During summer conditions, the temperature of the CO_2 at the pipeline outlet will be slightly higher and the pressure will also be slightly higher. Table 5.2 contains a summary of the pipeline design and assumptions and results.

5.2.2 WELL DESIGN

The reservoir modeling discussed in Appendix 3-1 determined that one horizontal injection well with an extended lateral of ~3937 feet (1,200 m) will be required to achieve the anticipated CO_2 injection rate at. Due to the need to provide casing through the Confining Zone and into the lateral section, three casing strings are necessary to complete the well. These include surface casing set below the USDW, protection casing set into the top of the Confining Zone, and a longstring casing set into the Injection Interval. The injection tubing will be set inside the longstring casing. A detailed description of the well construction and testing procedures will be presented later in this section. The drilling program is provided in Appendix 5-1. The directional plan is provided in Appendix 5-2.

As shown in the well schematic (Figure 5.1), the completion in the Injection Interval will be an openhole extended lateral into the Mt. Simon Sandstone that extends 3,937 feet long in the lateral section.

The sections below describe the injection well design, including wellhead injection pressure requirements, the casing and tubing specifications, the cementing program, packer design, annular fluid design, wellhead design, and well completion. "Schematic of the Subsurface Construction Details of the Well" provides a schematic of the downhole design and construction details of the injection well(s).

AVERAGE AND MAXIMUM WELLHEAD INJECTION PRESSURE

As mentioned in "Daily Rate and Volume and/or Mass and Total Anticipated Volume and/or Mass of the CO_2 Volume", the Lorain County Landfill is designed to inject at a maximum instantaneous injection rate of 387 MT/day which is derived from injecting 120,000 MT over 310.25 days (maximum operating days at 85% operational during the calendar year). As discussed in the Section 5.2.2 introduction, the current design basis is for one horizontal injection well. A steady-state, one-dimensional flow model with three components (water, NaCl, and CO_2) and four phases (aqueous, liquid CO_2, gaseous CO_2, and salt) with no flow boundaries on all sides was conducted to provide the pressure buildup and CO_2 plume models to determine the design and amount of injection wells needed for injecting 120,000 MT/yr.

To achieve the target injection rate, the injection pressure must be greater than the minimum bottomhole pressure required to drive the CO_2 into the reservoir formation, but the injection pressure must be maintained below the maximum safe pressure to avoid fracturing. The minimum bottom-hole pressure to provide the required flow rate into the Mt. Simon Sandstone was determined by reviewing typical fracture gradients for the Mt. Simon Sandstone from geologic literature (references found in Appendix 3-1). The maximum safe bottomhole pressure was specified as 90% of the rock's fracture pressure (0.9 X 0.65 psi/foot = 0.585 psi/foot) at the depth (4845 feet true vertical depth (TVD) top depth of open hole section) where the CO_2 is injected. The fracture pressure is based on geologic data from offset wells near the Lorain County Landfill. To be conservative, the required injection pressure was calculated based on the assumption that the required bottomhole pressure is equal to the maximum safe bottomhole pressure. These calculations are summarized in Table 5-3.

A pressure drop across a series of segments in the well including with a node at the top of the open-hole section (heel) and a node at the end of the lateral section (toe) was modeled using a steady-state, one-dimensional flow model. The CO_2 density is calculated from the pressure and temperature using the CO_2 equation of state by Span-Wagner (1996). The CO_2 will be assumed to be a liquid or supercritical fluid and the calculation stops if two-phase flow occurs. Two-phase flow was not modeled and is not anticipated to occur downhole in the injection well. The heat transfer will occur from the CO_2 stream into the Mt. Simon Sandstone, change in potential energy from the horizontal pipeline to the vertical injection tubing, and kinetic energy of the flow. The effective heat conductance is greatest when CO_2 injection operations are initiated and then decreases as the reservoir formation near the wellbore approaches the fluid temperature at bottomhole conditions, eventually approaching zero effective heat transfer (adiabatic condition) after a certain amount of time of CO_2 injection.

A portion of the bottomhole pressure required to support flow into the rock is provided by the hydrostatic head created by the weight of the column of fluid in the well. This depends upon the fluid density which varies with pressure and temperature because of the compressibility of CO_2. Lower temperature at the wellhead increases fluid density and decreases the wellhead pressure required to provide the necessary bottomhole pressure. Friction pressure drop in the injection tubing must also be overcome. Friction pressure drop can be decreased with the aid of a plastic-lining which is planned to be installed in the internal diameter (ID) of the injection tubing. The well design should not require injection pressure greater than the pressure of the CO_2 at the outlet of the CO_2 pipeline to the wellhead such that supplemental compression at the well site is not necessary.

Wellhead injection pressures were calculated for a flow rate of 387 MT/day and 3 ½ inch injection tubing and a surface CO_2 temperature of 45°F and 90°F to represent the range of anticipated CO_2 temperature at the injection wells during winter and summer, respectively.

CASING AND TUBING PROGRAM

Based on the data presented in "Average and Maximum Wellhead Injection Pressure", the well design includes the 3 1/2 inch diameter tubing string. Based on this information, the casing string sizes and types were chosen. by conducting design for collapse, burst, tension, compression, and tensile strength based on setting depths and drilling scenarios.

Sensitive, Confidential, or Privileged Information

[redacted]

Sensitive, Confidential, or Privileged Information

[redacted]

CEMENTING PROGRAM

This section discusses the types and quantities of cement that will be used for each casing string. All casing strings will be cemented back to the surface in accordance with requirements of the Class VI regulation. The proposed cement types and quantities for each casing string are summarized in Table 5-5.

The 16 inch surface casing will be cemented with 865 sacks of a Class A (Halcem or equivalent) premium tail cement with 15.8 ppg density, and 1.175 feet^3/sack yield.

The 10 ¾ inch intermediate casing will be cemented with 2200 sacks of a Class H (NeoCem or equivalent) premium tail cement with 15.0 density, and 1.345 $feet^3$/sack yield.

The 7 inch longstring casing will be cemented back to surface in two stages. The stage tool will be set at 4,400 feet and cemented as follows: Stage 1: 5000 feet to 4400 feet with 31.5 bbls of CO_2-resistant cement (WellLock or equivalent) with 9.2 density and Stage 2: 895 sacks of Class H (NeoCem or equivalent) premium tail cement with 15.0 ppg density, and 1.345 $feet^3$/sack yield.

The cementing details are presented in Appendix 5-3.

PACKER

Class VI regulations require that the CO_2 be injected through tubing that is secured to an injection packer installed inside the 7" longstring casing close to the casing shoe. The injection packer provides multiple functions in the well. First, the packer provides a means of anchoring the injection tubing string inside the 7 inch longstring casing. Second, the packer provides structural stability for the injection tubing and isolation of the annular space from the Injection Interval so that the annulus fluid (and pressure placed on the casing-tubing annulus) can be monitored for injection tubing, injection packer, or casing leaks in the well.

The packer will be installed inside the 7 inch longstring casing at approximately 15 feet (at 4,430 feet) above the longstring casing shoe which is approximately 200 feet above the top of the Injection Interval. The packer will be rated to withstand the differential pressure that it will experience during installation, workovers, and the injection phase.

The injection packer that is installed will be either a Halliburton HF-1 Feed-Through Packer or Weatherford BlackCat Retrievable Seal-Bore Packer (or similar). Both packers are retrievable. The Halliburton packer has a feed-thru system for the pressure-temperature sensor wiring and fiber optic wiring that are planned to be installed in the casing-tubing annulus.

In order to withstand the corrosion effects of CO_2 injection, the internal wetted parts of the packer will be made of 13 Chrome material, the same material in the 7" longstring casing below the stage tool, or nickel-plated. In addition, the packers will be manufactured using CO_2-compatible elastomer material (e.g. nitrile rubber).

The injection packer will have an on/off tool installed just above the packer so that the injection tubing string can be removed without removing the injection packer. To remove the injection tubing, rotate the injection tubing one-quarter turn at tool depth to shear the pins and release the injection tubing from the packer.

The Halliburton HF-1 packer is set on the bottom of the injection tubing while running the injection tubing into the well. The packer slips are set when the tubing pressure reaches 4,500 psig. During setting, there is no body movement and a hydraulically activated interlock mechanism prevents premature setting. The pressure and temperature gauges (and associated control line) and fiber optic line are lowered to with the injection packer and injection tubing at this time. The packer features premium thread connections for a tight seal to the injection tubing. The packer can also be installed in a horizontal well which will be the case for this well design. In addition the packer is designed to mitigate the up/down movement for the injection string during CO_2 injection operations.

The packer pressure differential rating is 7,500 psi and the maximum working temperature is 275°F.

ANNULAR FLUID

The annular space between the 7 inch longstring casing and the 3 ½ inch injection tubing will be filled with fluid to structurally support the injection tubing. The fluid pressure measured at the surface in the annulus will be maintained such that to exceed 100 psig above the maximum surface injection pressure.

Maintaining an overbalanced pressure system between the casing-tubing annulus pressure and the injection tubing pressure will support tubing or packer leak detection and provide a pressure safety cushion should a tubing leak occur. With the injection packer set at 4,430 feet, the volume of the annular space will be approximately 117 bbls (4,914 gal).

The annular fluid will be brine solution such as potassium chloride (KCl), sodium chloride (NaCl), calcium chloride ($CaCl_2$), or a similar solution. The fluid will be mixed on site with a 10 ppg density brine and cut down with freshwater (8.33 ppg). The freshwater will be filtered to remove solids, especially if taken from a pond. The final choice of the type of fluid will depend on availability.

The packer fluid (annular brine solution) will contain additives and inhibitors such as corrosion inhibitor, biocide (to prevent harmful bacteria growth), and an oxygen scavenger. Example additives and inhibitors are listed below with the approximate mix rates:

- TETRAHib Plus (corrosion inhibitor for carbon steel tubulars (casing and injection tubing) – 10 gal per 100 bbls of packer fluid
- CORSAF SF (corrosion inhibitor for use with 13Cr stainless steel tubulars or a combination of stainless steel and carbon steel tubulars) – 20 gal per 100 bbls of packer fluid
- Spec-cide 50 (biocide) – 1 gal per 100 bbls of packer fluid
- Oxban-HB (non-sulfide oxygen scavenger) – 10 gal per 100 bbls of packer fluid

These products were recommended and provided by Tetra Technologies, Inc., of Houston, Texas. The actual products used may vary and differ from those described above.

WELLHEAD

The wellhead and Christmas tree assembly (Figure 5.2) consists of the following components, from bottom to top:

Sensitive, Confidential, or Privileged Information

[redacted]

The wellhead and Christmas tree will be composed of materials that are compatible with the injection fluid (CO_2) to minimize corrosion. All components that come into contact with the CO_2 injection fluid will be made of a corrosion-resistant alloy such as stainless steel (13 Chrome). Because the CO_2 injection fluid will be very dry, use of stainless steel components for the flow-wetted components is a conservative measure to mitigate corrosion and increase the life expectancy of this equipment. Materials that do not encounter the injection fluid will be comprised of carbon steel material. All materials will comply with the API Spec 6A – Specification for Wellhead and Christmas Tree Equipment.

WELL OPENINGS TO FORMATION

The final construction of the well will be a horizontal well completion. The preferred completion type is open-hole into the Mt. Simon Sandstone. The 7-inch casing will be set at into Mt. Simon in a horizontal completion at 4,845 feet TVD (~5000 feet MD). The Mt. Simon Sandstone is expected to be 120 feet thick and the expected best layer (in terms of porosity and permeability) is near the 4,845 feet TVD depth. The lateral completion will extend from 5,000 feet MD to 8,937 feet MD.

An injection test will be conducted to determine if an acid stimulation if necessary. The acid stimulation would consist of hydrochloric acid containing additives such as surfactants, clay stabilizers, and iron sequestering agents which are allowed to soak in the formation for a pre-determined (typically 30 minutes) amount of time and then displaced with brine or potassium chloride (KCl) fluid.

The results of the characterization activities and the well completion will be described in the Well Completion Report that will be submitted to EPA after completion of the injection well drilling and characterization activities.

SCHEMATIC OF THE SUBSURFACE CONSTRUCTION DETAILS OF THE WELL

As discussed in the previous sections, the injection well will be a horizontal completion with the following casing strings: a 24-inch conductor string set at a depth of approximately 200 feet BGL; a 16 inch surface casing string set at approximately 1650 feet BGL; a 10 ¾ inch intermediate casing set at approximately 4445 feet BGL, and a 7 inch longstring casing set at a depth of 5000 feet MD (4845 feet TVD). The schematic of the injection well is included below as Figure 5.1. All depths are preliminary and will be adjusted based on additional characterization data obtained while drilling the CO_2 injection well and monitor wells.

The purpose of the conductor string is to provide a stable borehole across the near-surface, before drilling the deeper holes for the remaining casing strings and to help protect the USDWs in these formations. Groundwater in the locality of the site is normally obtained from sand and gravel deposits in the depth range of 750 and 800 feet MSL (1535 and 1585 feet BGL).

The surface string will extend across the main USDW (base of USDW at 1585 feet BGL) and protect the USDW from potential oil and gas-bearing zones in the strata. The intermediate casing will extend across and isolate deeper potentially unstable layers and formations above and into the Confining Zone. The longstring casing will protect the Confining Zone and top of Injection Zone into the Mt. Simon Sandstone to isolate CO_2 injection from formations above it.

6 PRE-OPERATIONAL LOGGING AND TESTING

For a Class VI Permit, a proposed pre-operational well and formation testing program is required to verify proper construction of the well and obtain an analysis of the chemical and physical characteristics of the injection and confining zones per 40 CFR 146.82 (a) (8). This program must also meet the requirements of 40 CFR 146.87, which includes elements related to both site characterization and well integrity.

The pre-operational logging and testing information is provided in the Class VI UIC Pre-Operational Testing.

6.1 WELL OPERATION

6.1.1 OPERATIONAL PROCEDURES [40 CFR 146.82(A)(10)]

The Operational Procedures is discussed above in Section 5.2.1.

6.1.2 PROPOSED CARBON DIOXIDE STREAM [40 CFR 146.82(A)(7)(III) AND (IV)]

The proposed Carbon Dioxide Stream is discussed above in Section 5.2.1.

7 TESTING AND MONITORING

Class VI permit applicants must submit a Testing and Monitoring Plan, provided in the Class VI UIC Project Plan Submissions. Per 40 CFR 146.82 (a) (15), this plan must meet the requirements of 40 CFR 146.90.

8 INJECTION WELL PLUGGING

Class VI permit applicants must submit an Injection Well Plugging Plan, provided in the Class VI UIC Project Plan Submissions. This plan must meet the requirements of 40 CFR 146.92 [40 CFR 146.82 (a) (16)]. The cost associated with the Class VI well closure is provided in the Class VI UIC Project Plan Submissions.

9 POST-INJECTION SITE CARE (PISC) AND SITE CLOSURE

Class VI permit applicants must submit an PISC and Site Closure Plan, provided in the Class VI UIC Project Plan Submissions. This plan must meet the requirements of 40 CFR 146.82 (a) (17) – (18) and 40 CFR 146.93.

10 EMERGENCY AND REMEDIAL RESPONSE

Class VI permit applicants must submit an Emergency and Remedial Response Plan, provided in the Class VI UIC Project Plan Submissions. This plan must meet the requirements of 40 CFR 146.82 (a) (19) and 40 CFR 146.94.

11 INJECTION DEPTH WAIVER AND AQUIFER EXEMPTION EXPANSION

Class VI permit applicants must submit a waiver application report, which meets the requirements of 40 CFR 146.95 (a) (1) – (7).

This section is not applicable to this permit application.

12 OTHER INFORMATION

12.1 ACRONYMS

AOR	Area of Review
APs	Artificial Penetrations
APT	Annulus Pressure Test

BGL	Below Ground Level
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DNR	Department of Natural Resources
DOGRM	Division of Oil and Gas Resources Management
EOR	Enhanced Oil Recovery
EPA	U.S. Environmental Protection Agency
FJ	Flush Joint
GHGs	Green House Gases
GPC	Groundwater Protection Council
gpm	gallons per minute
ID	Internal Diameter
km	Kilometers
md	Millidarcy
MD	Measured Depth
MSL	Mean Sea Level
NEIC	National Earthquake Information Center
ODNR	Ohio Department of Natural Resources
PE	Plain End
PISC	Post-Injection Site Closure
TVD	True Vertical Depth
TDS	Total Dissolved Solids
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
USGS	United States Geological Survey

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12.3 LIST OF TABLES, FIGURES, AND APPENDICES

TABLES

FIGURES

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TABLES

TABLE 1-1

GENERAL CLASS VI WASTE INJECTION WELL PERMIT APPLICATION INFORMATION

Injection Well Information	
Well Name and Number	Well No. CCS #1
County	Lorain County, Ohio
Section	Section 79
Location (US STP NAD27 Ohio North) TYPE_EASTING(X)_NORTHING(X)	Surface_2087845_595505.8 Heel_2088075_595833.5 Toe_2090333_599058.5
Owner Information	
Name	Lorain Carbon Zero Solutions, LLC
Address	43502 Oberlin-Elyria Road Oberlin, Ohio 44074
Ownership Status	Private
All activities conducted by the applicant which require permits	Not Applicable
Operator Information	
Name	Lorain Carbon Zero Solutions, LLC
Address	43502 Oberlin-Elyria Road Oberlin, Ohio 44074
Operator's Status	Private
All permit or construction approvals	Not Applicable
Facility/Site Information	
Facility Name	Lorain County Landfill
Facility Address	43520 Oberlin-Elyria Road Oberlin, Ohio 44074
Facility Phone Number	440-774-4060
Related Standard Industrial Classification (SIC) Codes	The Geologic Sequestration Rule asks for the identification of up to four SIC codes, reflecting the best principal products or services provided by the facility. A SIC code has not been established for geologic sequestration of CO_2. SIC Code 4922 is Natural Gas Transmission, and includes natural-gas storage (OSHA, 2012b, a). Natural-gas storage is similar to CO_2 storage.
Facility Located on Indian Lands?	No

TABLE 2-1
ALL EARTHQUAKES 1900 TO PRESENT IN THE OHIO REGION

Date (YYYY-MM-DD)	Latitude	Longitude	Epicenter Depth (km)	Magnitude	Location Description
2021-01-22	40.724	-84.1712	6.68	2.4	5 km NW of Fort Shawnee, Ohio
2020-10-08	38.8388333	-82.7571667	13.62	2.29	3 km NW of South Webster, Ohio
2020-08-21	41.9125	-83.3179	9.2	3.2	2 km SSE of Detroit Beach, Michigan
2020-07-14	40.4165	-84.0876	9.78	2.3	4 km WSW of Jackson Center, Ohio
2020-07-14	40.4403	-84.0865	9.64	1.8	Ohio
2020-04-07	41.7952	-81.1234	5	2.2	4km NNE of Perry, Ohio
2019-12-11	41.7215	-81.4316	5	2	6km WNW of Mentor-on-the-Lake, Ohio
2019-12-10	41.6829	-81.4821	5	1.7	4km NW of Eastlake, Ohio
2019-12-07	41.6481	-81.4715	5	2.6	1km WSW of Eastlake, Ohio
2019-10-15	41.7284	-81.0516	5	2.6	4km S of Madison, Ohio
2019-06-17	41.6655	-81.4876	5	1.6	3km WNW of Eastlake, Ohio
2019-06-15	41.6891	-81.478	5	1.8	4km NNW of Eastlake, Ohio
2019-06-10	41.6797	-81.4564	2	4	2km N of Eastlake, Ohio
2019-03-06	41.4592	-81.6529	5	2	1km NE of Newburgh Heights, Ohio
2019-03-03	38.9033333	-83.8321667	12.66	2.48	7km NE of Georgetown, Ohio
2018-09-04	41.7131667	-81.043	5	1.55	6km S of Madison, Ohio
2018-07-31	41.8161667	-81.2666667	5	1.66	7km N of Fairport Harbor, Ohio
2018-01-26	39.4368	-81.7153	11.02	2.5	13km SSW of Beverly, Ohio
2017-06-26	38.7125	-83.7631667	15.44	1.59	6km N of Aberdeen, Ohio
2017-06-03	39.9166	-81.2934	1.73	3.4	12km SW of Barnesville, Ohio
2017-05-24	39.2296	-82.4759	10	3.4	1km S of McArthur, Ohio
2017-04-02	39.6644	-81.2434	3.93	3	15km SW of Woodsfield, Ohio
2017-01-23	38.5376	-82.3195	18.29	2	3km NNW of Lesage, West Virginia
2016-12-12	39.6578333	-81.2521667	8.57	2.22	16km SW of Woodsfield, Ohio
2016-12-12	39.6513333	-81.264	6.15	1.79	17km SW of Woodsfield, Ohio
2016-08-03	40.046	-81.2456667	1	1.98	8km NW of Barnesville, Ohio
2016-03-08	38.9045	-82.445	20	2.6	11km E of Oak Hill, Ohio
2016-02-07	41.6503	-82.8969	5	2.5	15km NNE of Port Clinton, Ohio
2015-09-30	40.22	-81.1903333	2	2.1	17km WSW of Cadiz, Ohio
2015-06-12	40.955	-84.762	5	2.6	6km NW of Convoy, Ohio
2015-04-12	41.7353333	-81.0115	5	2	5km SE of Madison, Ohio
2015-02-11	39.1496	-82.7375	20	2.6	13km NW of Jackson, Ohio
2014-08-31	41.196	-80.7765	2.56	1.98	1km WSW of Bolindale, Ohio
2014-04-08	41.8105	-81.0038	5	2.2	3km ENE of North Madison, Ohio
2014-03-11	41.0025	-80.5336667	5.22	1.86	3km S of Lowellville, Ohio
2014-03-10	41.009	-80.5316667	5	2.42	2km S of Lowellville, Ohio
2014-03-10	41.0096667	-80.53	5	2.16	2km S of Lowellville, Ohio
2014-03-10	41.0103333	-80.5433333	2.54	2.44	2km SSW of Lowellville, Ohio
2014-03-10	41.0088333	-80.555	5	1.97	3km SSW of Lowellville, Ohio
2014-01-28	41.876	-81.7128333	6.96	1.9	Lake Erie, Ohio
2014-01-20	41.4083	-81.9056	13	2.1	1km ESE of North Olmsted, Ohio
2013-11-20	39.445	-82.205	8	3.5	2km ESE of Nelsonville, Ohio
2013-10-06	41.8026667	-80.9948333	5	1.88	4km WSW of Geneva-on-the-Lake, Ohio
2013-10-02	40.239	-81.257	2	2.08	Ohio
2013-07-01	41.793	-81.292	5	3.2	6km NW of Fairport Harbor, Ohio
2013-03-27	38.668	-82.215	15.4	2.5	15km S of Gallipolis, Ohio
2013-03-17	41.6575	-80.8946667	5	1.86	6km WNW of Roaming Shores, Ohio
2013-03-08	41.71	-81.467	5	2.7	Lake Erie, Ohio
2013-02-17	42.018	-82.224	5	2.5	southern Ontario, Canada
2012-09-07	41.864	-83.076	5.1	2.5	Ohio
2012-01-13	41.1245	-80.6923333	5.79	1.74	Youngstown-Akron urban area, Ohio
2011-12-31	41.1215	-80.6843333	5	4	Youngstown-Akron urban area, Ohio

TABLE 2-1
ALL EARTHQUAKES 1900 TO PRESENT IN THE OHIO REGION

2011-12-24	41.1225	-80.7046667	5	2.37	Youngstown-Akron urban area, Ohio
2011-11-25	41.124	-80.6771667	5	1.79	Youngstown-Akron urban area, Ohio
2011-10-20	41.1253333	-80.704	6.39	2.04	Youngstown-Akron urban area, Ohio
2011-09-30	41.1346667	-80.6845	5	2.44	Youngstown-Akron urban area, Ohio
2011-09-26	41.115	-80.6823333	5	2.12	Youngstown-Akron urban area, Ohio
2011-09-04	39.422	-81.205	5	2.6	Ohio
2011-08-31	39.51	-81.47	5	3.1	Ohio
2011-08-31	39.4	-81.27	5	2.8	Ohio
2011-08-22	41.1303333	-80.7081667	5	1.87	Youngstown-Akron urban area, Ohio
2011-08-13	42.0771667	-81.0005	5	1.34	Lake Erie, Ohio
2011-06-05	41.03	-82.08	5	3	Ohio
2011-04-26	40.86	-83.54	5	2.4	Ohio
2011-03-17	41.126	-80.6056667	3.54	2.1	Ohio
2010-10-24	39.433	-81.362	5	2.8	Ohio
2010-06-10	41.76	-81.43	5	2.6	Lake Erie, Ohio
2010-06-07	41.77	-81.1	5	2.4	Ohio
2010-05-17	41.24	-81.51	5	2.7	Ohio
2010-05-14	41.39	-83.3	5	2.7	Ohio
2010-04-25	41.78	-81.08	5	3	Ohio
2010-02-25	41.22	-83.29	5	2.4	Ohio
2009-04-24	38.81	-82.27	5	3.3	13km NW of Gallipolis, Ohio
2009-02-14	41.84	-81	5	2.6	Ohio
2008-09-30	40.41	-84.31	5	2.8	Ohio
2008-09-18	41.78	-81.43	5	2.9	Lake Erie, Ohio
2008-01-26	41.7996667	-81.0025	8.5	1.83	Ohio
2008-01-09	41.72	-81.43	5	3.1	Lake Erie, Ohio
2007-10-17	41.75	-81.42	5	3.4	Lake Erie, Ohio
2007-09-28	41.9685	-80.5673333	7.66	2.13	Lake Erie, Ohio
2007-09-28	41.9688333	-80.5791667	6.72	2.69	Lake Erie, Ohio
2007-04-12	41.722	-82.924	5	2.8	Lake Erie, Ohio
2007-03-12	41.28	-81.38	5	3.7	Ohio
2006-08-15	40.71	-84.11	5	2.5	Ohio
2006-06-20	41.84	-81.23	5	3.5	Lake Erie, Ohio
2006-05-12	40.74	-84.08	5	2.8	Ohio
2006-04-10	41.9685	-80.8226667	10	1.96	Lake Erie, Ohio
2006-03-27	41.7901667	-81.447	7.84	2	Lake Erie, Ohio
2006-03-11	41.78	-81.39	5	3.1	Lake Erie, Ohio
2006-02-10	41.75	-81.41	5	2.6	Lake Erie, Ohio
2006-01-13	41.8	-81.45	7	2.3	Lake Erie, Ohio
2006-01-06	41.77	-81.45	5	2.6	Lake Erie, Ohio
2005-12-11	41.954	-80.802	9.97	2	Lake Erie, Ohio
2005-11-13	41.816	-81.18	5	2.2	Lake Erie, Ohio
2005-03-13	40.67	-84.62	5	2.2	Ohio
2004-06-30	41.78	-81.08	5	3.3	Ohio
2004-03-14	41.77	-81.24	5	2.4	Lake Erie, Ohio
2004-01-30	40.67	-84.65	5	2.5	Ohio
2003-07-17	41.86	-80.76	2.5	2.5	Ohio
2003-06-30	41.8	-81.2	4.6	3.6	Lake Erie, Ohio
2002-05-06	38.948	-81.889	5	2.8	Ohio
2002-04-28	41.85	-81.37	5	2.7	Lake Erie, Ohio
2001-06-03	41.905	-80.767	5	3.4	Ohio
2001-01-26	41.942	-80.802	5	3.9	Lake Erie, Ohio
2001-01-20	41.877	-80.774	5	2.6	Ohio
2000-08-07	40.958	-81.151	5	2.9	Ohio

TABLE 2-1

ALL EARTHQUAKES 1900 TO PRESENT IN THE OHIO REGION

1999-09-22	41.826	-81.476	18	2.8	Lake Erie, Ohio
1998-11-25	41.071	-82.405	5	2.7	Ohio
1995-02-23	41.87	-80.83	5	2.9	Ohio
1995-02-19	39.12	-83.47	10	3.6	Ohio
1994-04-04	40.4	-84.4	5	2.9	Ohio
1993-10-16	41.698	-81.012	5	3.6	Ohio
1992-03-15	41.911	-81.245	5	3.5	Lake Erie, Ohio
1991-01-26	41.536	-81.453	5	3.4	Cleveland urban area, Ohio
1990-06-04	41.098	-83.638	5	2.5	Ohio
1988-05-28	39.753	-81.613	0	3.4	Ohio
1987-07-16	41.9	-80.8	5	2.7	Ohio
1987-07-14	41.9	-80.8	5	2.8	Ohio
1987-07-13	41.9	-80.8	5	2.9	Ohio
1987-07-13	41.9	-80.8	5	3	Ohio
1987-07-13	41.896	-80.767	5	3.5	Ohio
1986-07-12	40.537	-84.371	10	4.5	Ohio
1986-02-07	41.645	-81.157	6.2	2.5	Ohio
1986-01-31	41.65	-81.162	10	5	Ohio
1984-01-14	41.645	-83.427	5	2.5	Ohio
1983-01-22	41.854	-81.191	5	2.7	Lake Erie, Ohio
1980-08-20	41.941	-83.01	5	3.2	Ohio
1977-06-17	40.707	-84.582	5	3.2	Ohio
1976-02-02	41.96	-82.67	10	3.4	Ohio
1975-02-16	39.05	-82.422	5	3.3	Ohio
1974-09-29	41.238	-83.361	1	3	Ohio
1952-06-20	39.64	-82.023	9	4	Ohio
1943-03-09	41.628	-81.309	7	4.5	Ohio
1937-03-09	40.47	-84.28	3	5.4	Ohio
1937-03-02	40.488	-84.273	2	5	Ohio
1931-09-20	40.429	-84.27	5	4.7	Ohio
1930-09-30	40.3	-84.3		4.2	Ohio
1926-11-05	39.1	-82.1		3.8	Ohio
1901-05-17	38.75	-83		4.2	Ohio
1900-04-09	41.4	-81.9		3.4	Cleveland urban area, Ohio

Source: https://www.usgs.gov/natural-hazards/earthquake-hazards/science/information-region-ohio?qt-science_center_objects=0#qt-science_center_o

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

TABLE 3-1

4.4-MILE AREA OF REVIEW

Sensitive, Confidential, or Privileged Information

[redacted]

Table 5.1 CO_2 Acceptance Specifications

Component	Quality
CO_2	89 percent dry basis
Methane	2 percent
Nitrogen	5 percent
Oxygen (O_2)	2 percent
Water	2 percent
Arsenic	<5.0 ppm (5.0 mg/L)[a]
Selenium	<1.0 ppm (1.0 mg/L)[a]
Mercury (Hg)	<2 ppb[b]
Hydrogen Sulfide (H_2S)	<20 ppm[c]
VOCs and siloxanes	Trace amounts

(a) This is the Resource Conservation and Recovery Act (RCRA) standard

(b) This is the Safe Drinking Water Act standard.

(c) This is a standard specification for the pipeline quality CO_2. No detectible amounts of H_2S are expected in the CO_2 waste stream at the Lorain Landfill.

Table 5-2 Pipeline Design Assumptions and Results

Parameter	Receiving Meter Station	Delivery Meter Station
Pressure (psig)	1800	~1500
CO_2 Temperature (°F)	70	70
Mass Flow Rate (MMTA)	0.120	0.120
Flow Rate @ STP (mmscfd)	5.75	5.75
Actual Flow Rate (ft^3/d)	13,640	12,822
Density (lb/ft^3)	~35.9	~35.9
Viscosity (cp)	0.75	0.80
Molecular Weight	43.5	43.5

Table 5.3 Flow Rates and Limiting Pressure for Hydraulic Calculations

Parameter	One Injection Well
Depth Injection Interval (ft-TVD)	4,845
Flow Rate/well (MT/d)	387
Maximum bottom-hole pressure (psi) (injection depth * .585 psi/ft)	2,834

TABLE 5-4 TUBULAR SPECIFICATIONS - REPUBLIC LORAIN

TABLE 5-4A

Type	Outside Diameter	Grade	Weight	Wall Thickness	Joint Specification	Depth Interval	
						Top	Bottom
	[inch]	-	[lb/ft]	[inch]	-	[ft]	[ft]
Conductor	Sensitive, Confidential, or Privileged Information [redacted]						
Surface Casing							
Intermediate Casing							
Longstring Casing							
Longstring Casing (13 Chrome)							
Injection Tubing							

TABLE 5-4B

Section	Evaluate Location	Resistance				Loads				Factor of Safety			
		Collapse	Internal Yield	Joint Strength	Minimum Yield	Maximum External	Maximum Internal	Maximum Axial	Maximum Triaxial Stress on Pipe Body	Collapse	Burst	Joint Strength	Pipe Body Yield
		[psi]	[psi]	[lbf]	[psi]	[psi]	[psi]	[lbf]	[psi]				
Conductor	Top	Sensitive, Confidential, or Privileged Information [redacted]											
	Bottom												
	Reference												
Surface Casing	Top												
	Bottom												
	Reference												
Intermediate Casing	Top												
	Bottom												
	Reference												
Longstring Casing	Top												
	Bottom												
	Reference												
Longstring Casing (13 Chrome)	Top												
	Bottom												
	Reference												
Injection Tubing	Top												
	Bottom												
	Reference												

Note: Values for resistance to collapse, internal yield, and maximum triaxial stress on pipe body were determined using equations provided in API Technical Report 5C3 (2018), Calculating Performance Properties of Pipe Used as Casing or Tubing.

REFERENCE KEY

A	Values assume an external pressure of fresh water (0.433 psi/ft), internal pressure of air (0.001 psi/ft), and axial force equivalent to the Section weight with no buoyant forces.
B	Values assume an external pressure gradient equivalent to fresh water (0.433 psi/ft).
C	Joint strength of welded connection was approximated from the minimum yield strength of material.
D	Value reported by: API Specification 5L (2010): Specification for Line Pipe.
E	Assumes an external pressure of fresh water (0.433 psi/ft).
F	Pressure encountered during cementing of the subsequent string; assumes cement gradient (0.853 psi/ft) plus 100 psi at surface.
G	Assumes the full weight of casing with no buoyant forces.
H	External pressure of cement from top to bottom (0.853 psi/ft), internal pressure of fresh water (0.433 psi/ft), and axial force equivalent to the Section weight with no buoyant forces.
I	Values calculated from equations provided in API Technical Report 5C3 (2018), Calculating Performance Properties of Pipe Used as Casing or Tubing.
J	Value reported by: API Specification 5CT (2006), Spedcification for Casing and Tubing.
K	Internal surface pressure of 2,500 psi with a fluid of 0.473 psi/ft and no external pressure.
L	External surface pressure of 2,600 psi with a fluid of 0.473 psi/ft, internal pressure of air (0.001 psi/ft), and an axial force equivalent to the Section weight plus 40,000 pounds.
M	Values assume an external pressure gradient of 0.473 psi/ft.
N	Assumes the full weight of casing plus 40,000 pounds.
O	Internal surface pressure of 2,500 psi (max wellhead pressure during CO2 injection) with a fluid of 0.473 psi/ft and no external pressure.

Table 5-5 Cementing Program

Casing	Size (inches)	Hole Size (inches)	Depth (feet)	Remarks
Conductor	Sensitive, Confidential, or Privileged Information [redacted]			
Surface				
Intermediate				
Production				

FIGURES

Sensitive, Confidential, or Privileged Information

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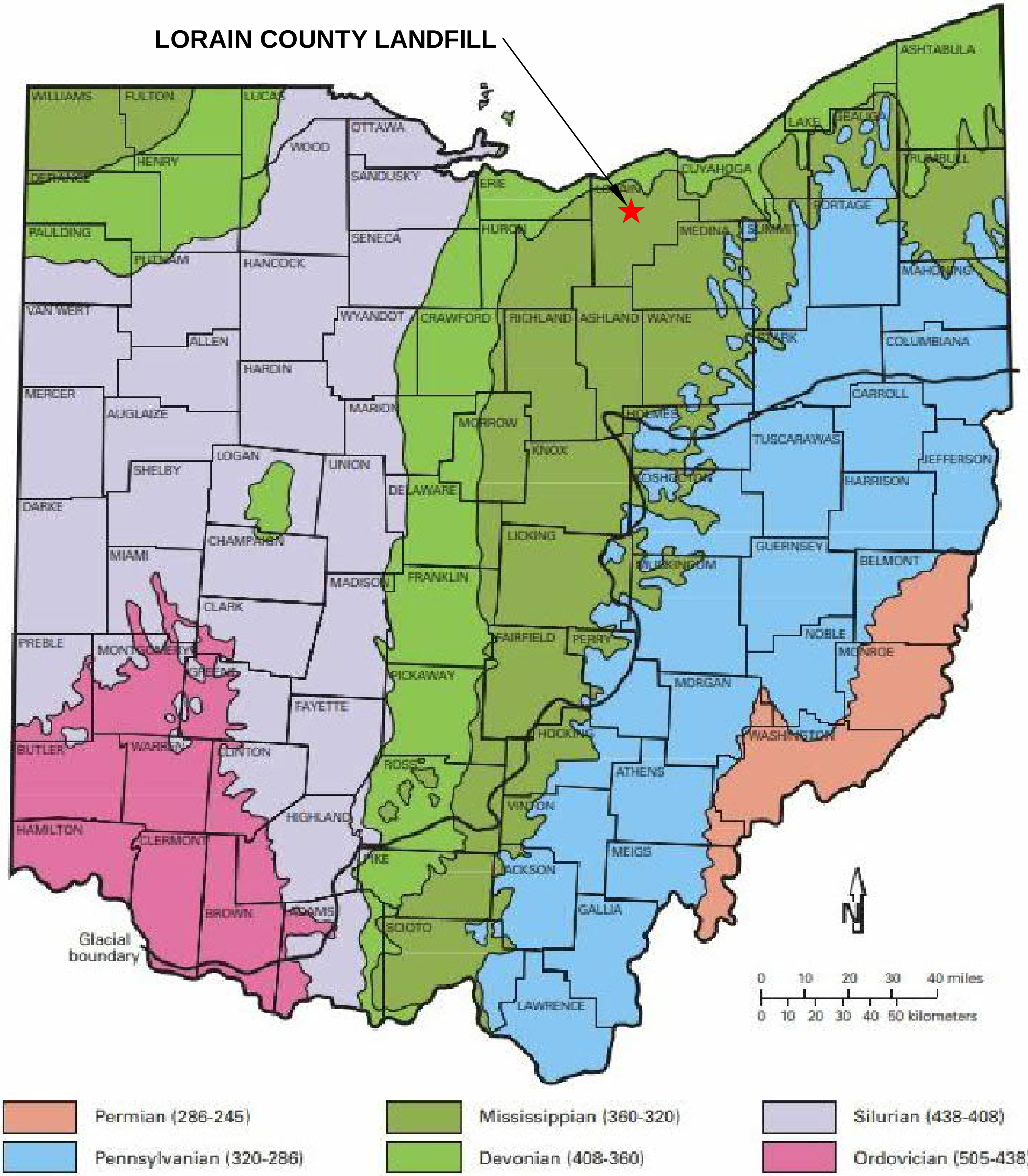


Source: Coogan, 1996

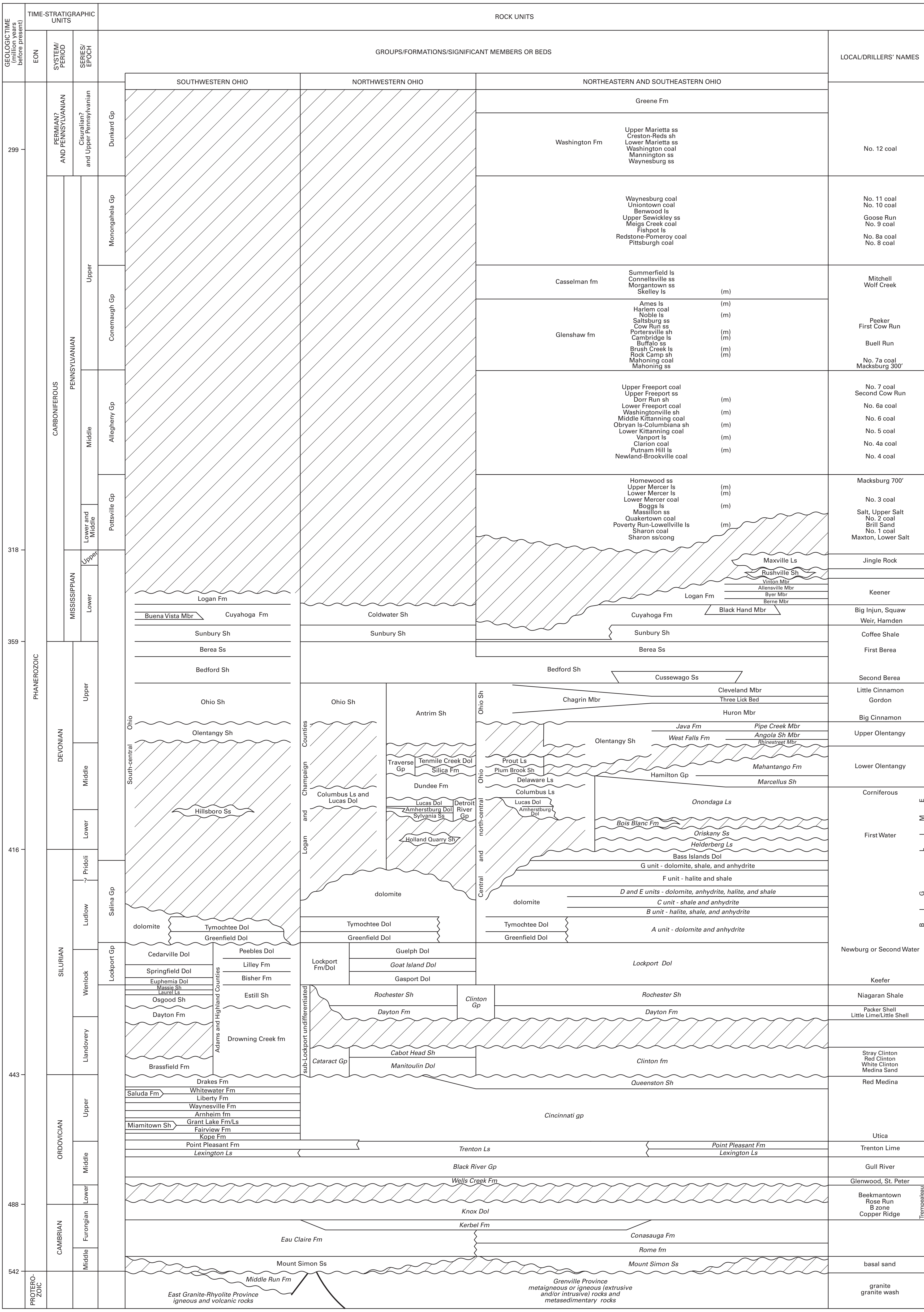
wsp	WSP USA Inc. 16200 Park Row, Ste. 200 Houston, TX 77084 TEL: (281) 589-5900	**LORAIN CARBON ZERO SOLUTIONS, LLC** **LORAIN COUNTY, OHIO**

REGIONAL GEOLOGIC MAP					Job No. 192128N
Drawn: WDD	Checked: MEC	Approved: GEM	Date: 03/01/2021	Scale: NONE	Figure No. 2-2

STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY

GENERALIZED COLUMN OF BEDROCK UNITS IN OHIO

Dennis N. Hull, chief compiler, 1990
revised by Glenn E. Larsen, 2000; Ernie R. Slucher, 2004



Compilation based on published, unpublished, and web-based sources and personal communications with staff of the Division of Geological Survey, the United States Geological Survey, and geological sciences departments at numerous mid-continent region universities. Time-stratigraphic divisions primarily from the International Commission on Stratigraphy (www.stratigraphy.org). Geologic time dates from: Gradstein, Ogg, Smith, et al, 2004, A Geologic Time Scale 2004: Cambridge University Press.

2/04

Drafted by Robert L. Stewart, Sr., Lisa Van Doren

Sh	shale	Dol	dolomite	Fm	Formation
Ss	sandstone	Cong	conglomerate	Mbr	Member
Ls	limestone	(m)	marine zone	Gp	Group

Depositional hiatus or interval removed by erosion

unconformity

Fault or tectonic zone

Note: Lower case lithologic or stratigraphic names indicate informal status of unit. Units found in the subsurface only are indicated in italics.

recycled paper

Recommended citation: Ohio Division of Geological Survey, 1990 (rev. 2000, 2004), Generalized column of bedrock units in Ohio: Ohio Department of Natural Resources, Division of Geological Survey, 1 p.

FIGURE 2-3

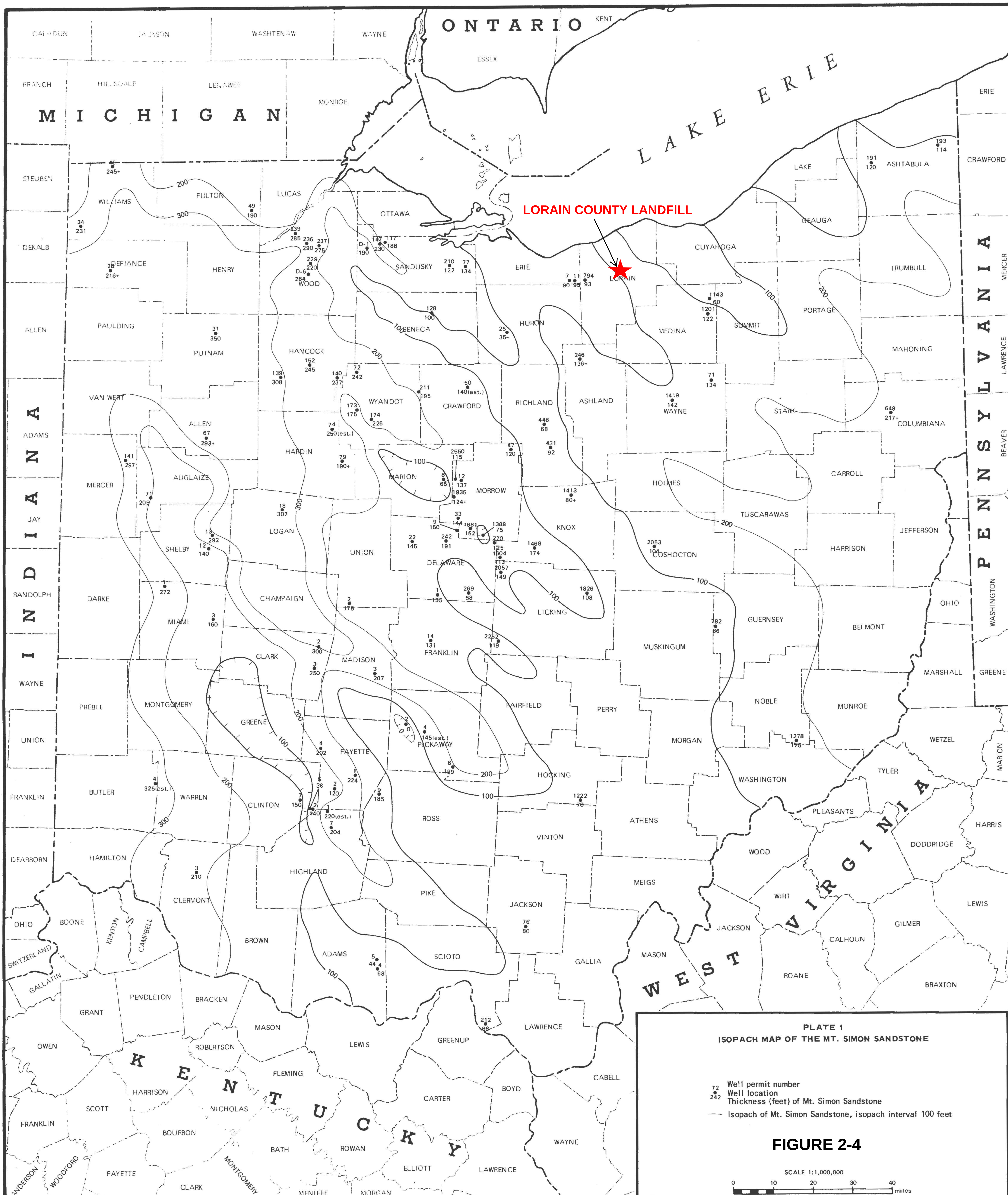


PLATE 1
ISOPACH MAP OF THE MT. SIMON SANDSTONE

72 242 Well permit number
Well location
Thickness (feet) of Mt. Simon Sandstone
Isopach of Mt. Simon Sandstone, isopach interval 100 feet

FIGURE 2-4

SCALE 1:1,000,000
0 10 20 30 40 miles

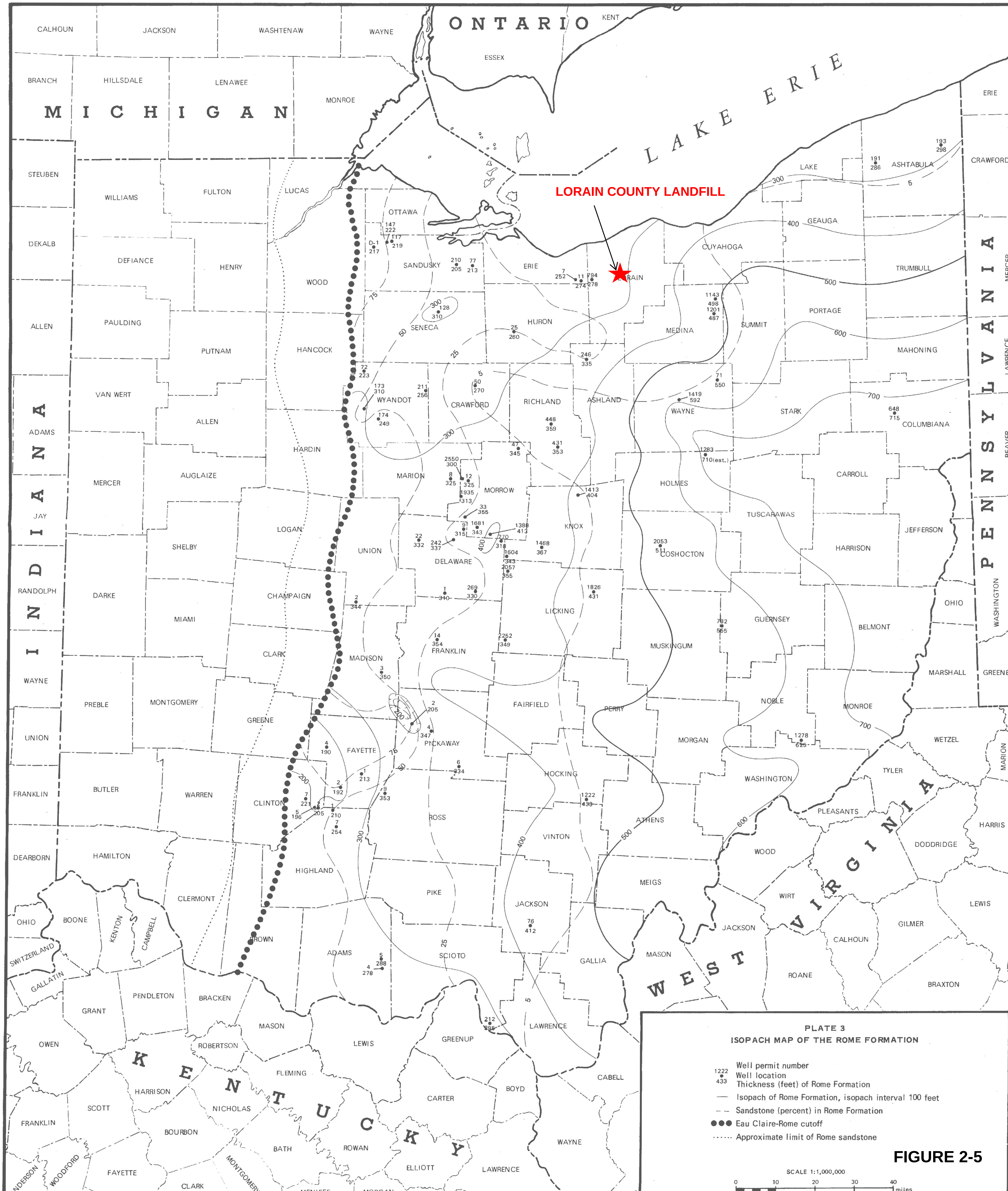

ONTARIO
LAKE ERIE
MICHIGAN
INDIANA
PENNSYLVANIA
WEST VIRGINIA
KENTUCKY
LORAIN COUNTY LANDFILL
PLATE 3
ISOPACH MAP OF THE ROME FORMATION
1222 Well permit number
Well location
433 Thickness (feet) of Rome Formation
Isopach of Rome Formation, isopach interval 100 feet
Sandstone (percent) in Rome Formation
Eau Claire-Rome cutoff
Approximate limit of Rome sandstone
SCALE 1:1,000,000
0 10 20 30 40 miles

FIGURE 2-5

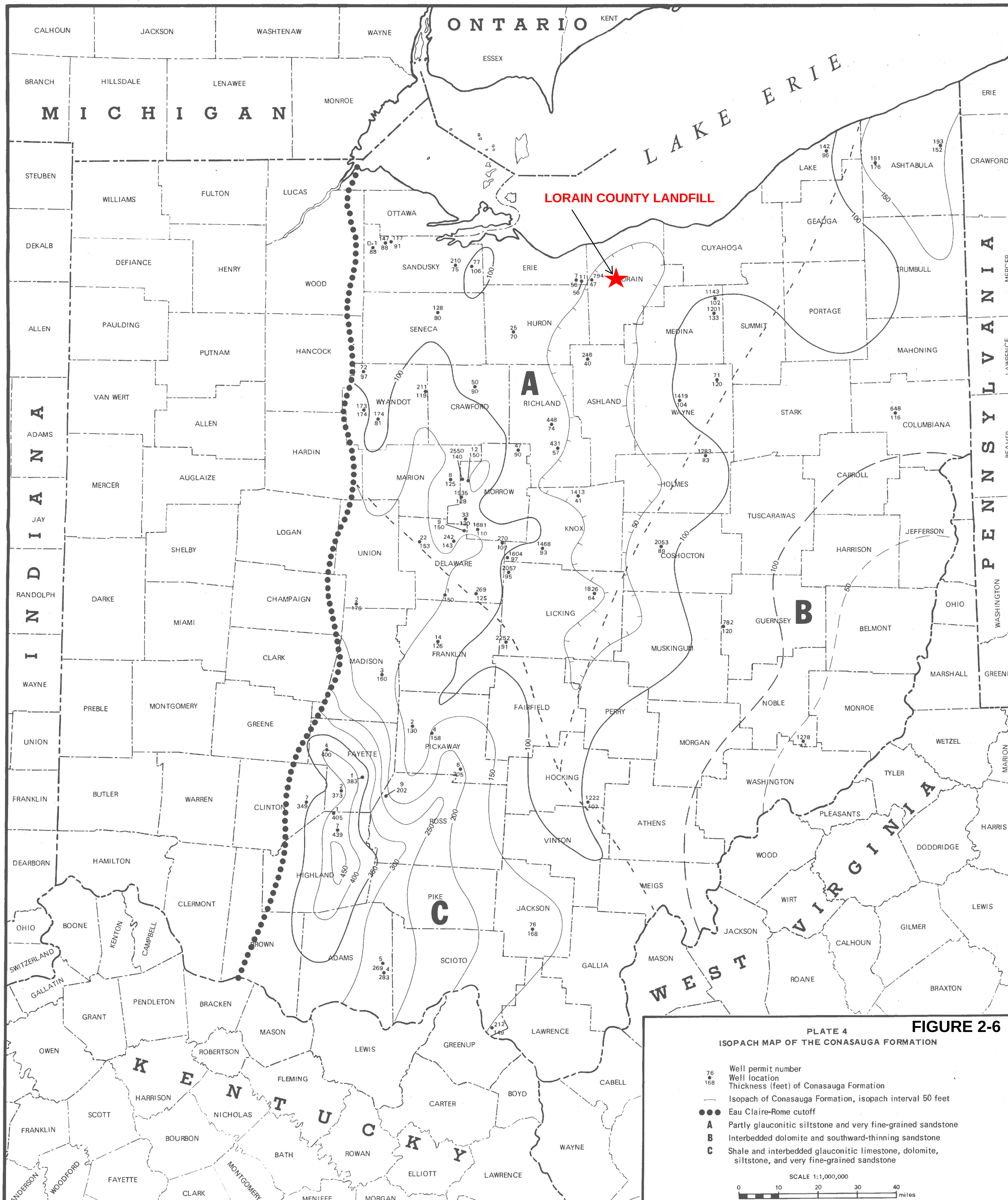

LORAIN COUNTY LANDFILL
ONTARIO
LAKE ERIE
MICHIGAN
INDIANA
PENNSYLVANIA
WEST VIRGINIA
KENTUCKY
A
B
C
PLATE 4
ISOPACH MAP OF THE CONASAUGA FORMATION
76 168 Well permit number
Well location
Thickness (feet) of Conasauga Formation
Isopach of Conasauga Formation, isopach interval 50 feet
Eau Claire-Rome cutoff
A Partly glauconitic siltstone and very fine-grained sandstone
B Interbedded dolomite and southward-thinning sandstone
C Shale and interbedded glauconitic limestone, dolomite, siltstone, and very fine-grained sandstone
SCALE 1:1,000,000
0 10 20 30 40 miles

FIGURE 2-6

Sensitive, Confidential, or Privileged Information

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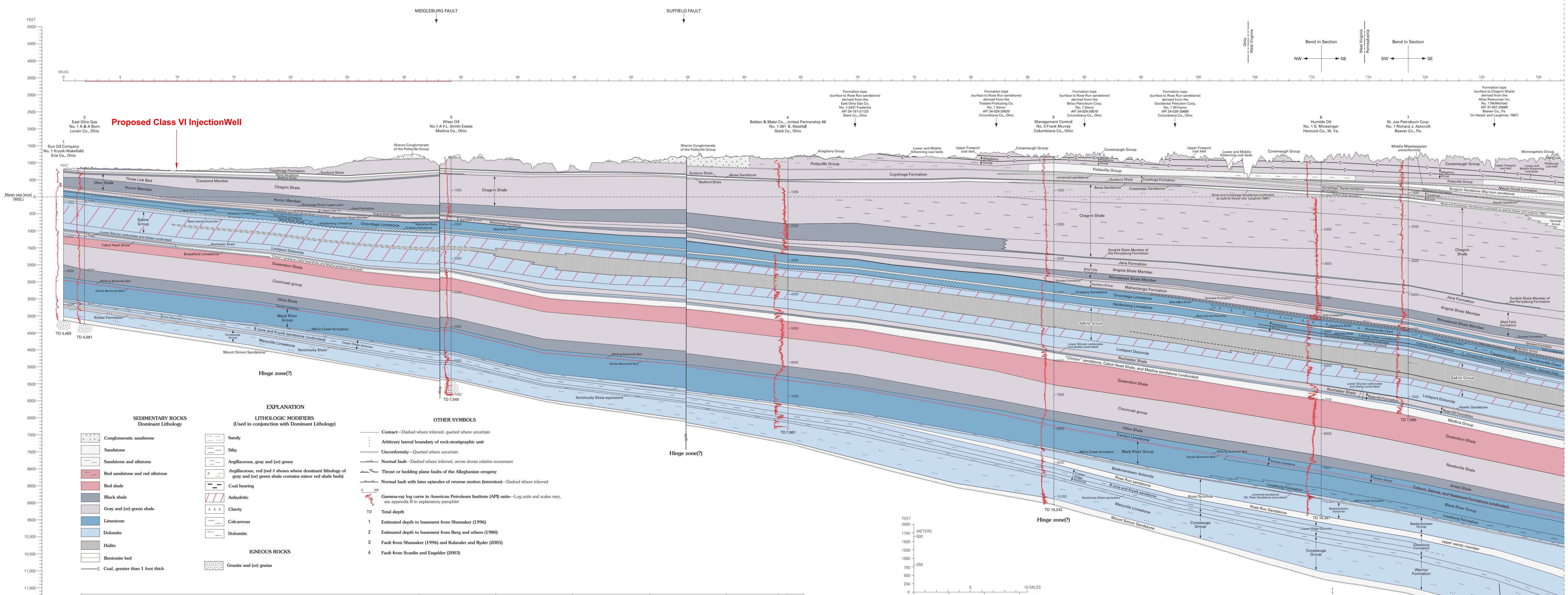


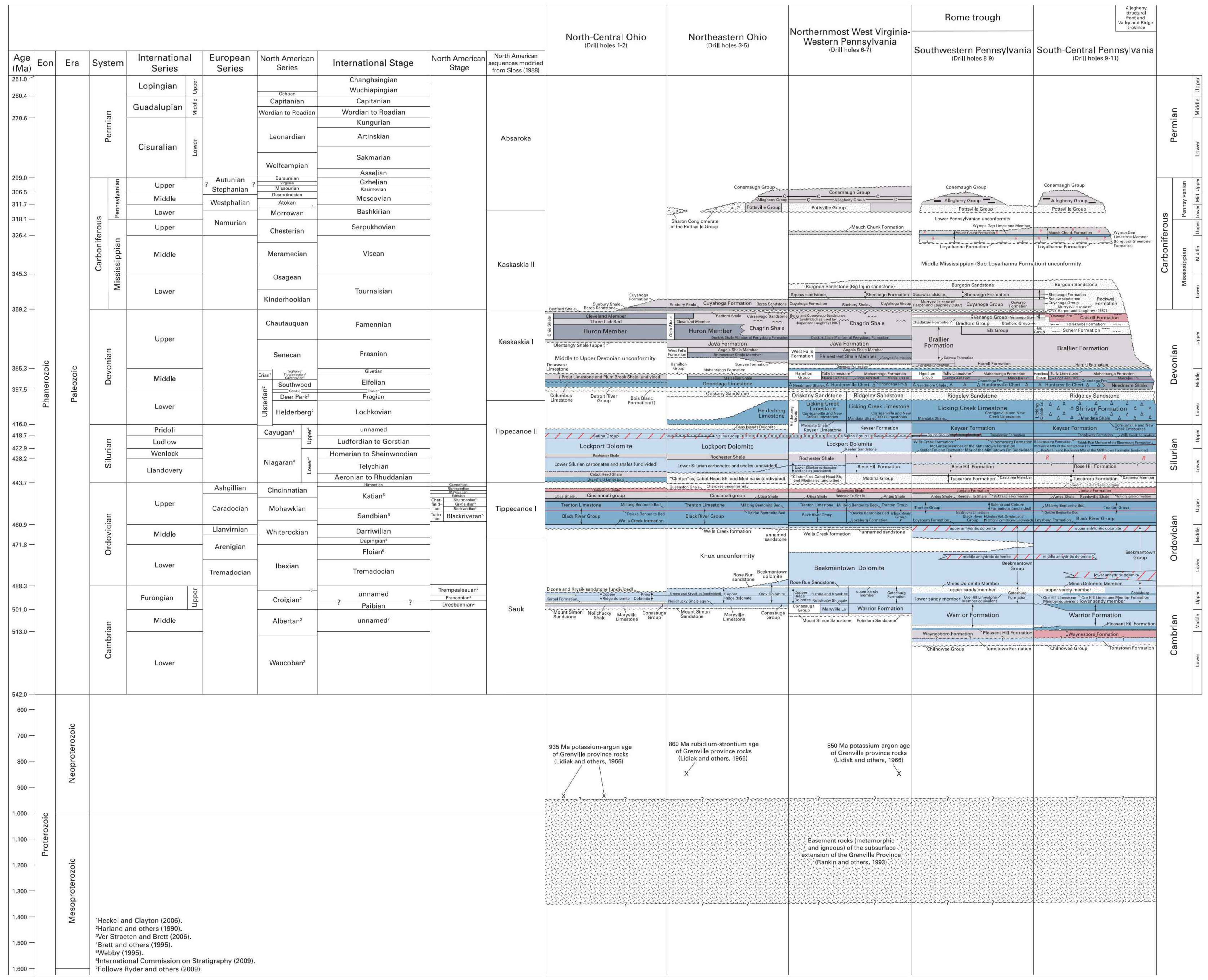


Figure 2.—Correlation chart of Paleozoic rocks along cross section C–C' in Ohio, northernmost West Virginia, and Pennsylvania. Geologic time scale from Gradstein and others (2004) except as noted. Abbreviations are as follows: equiv, equivalent; Fm, Formation; Gp, Group; Ls, Limestone; Ma, million years (mega-annum); mbr, member; Sh, Shale; ss, sandstone.

Lorain County Landfill

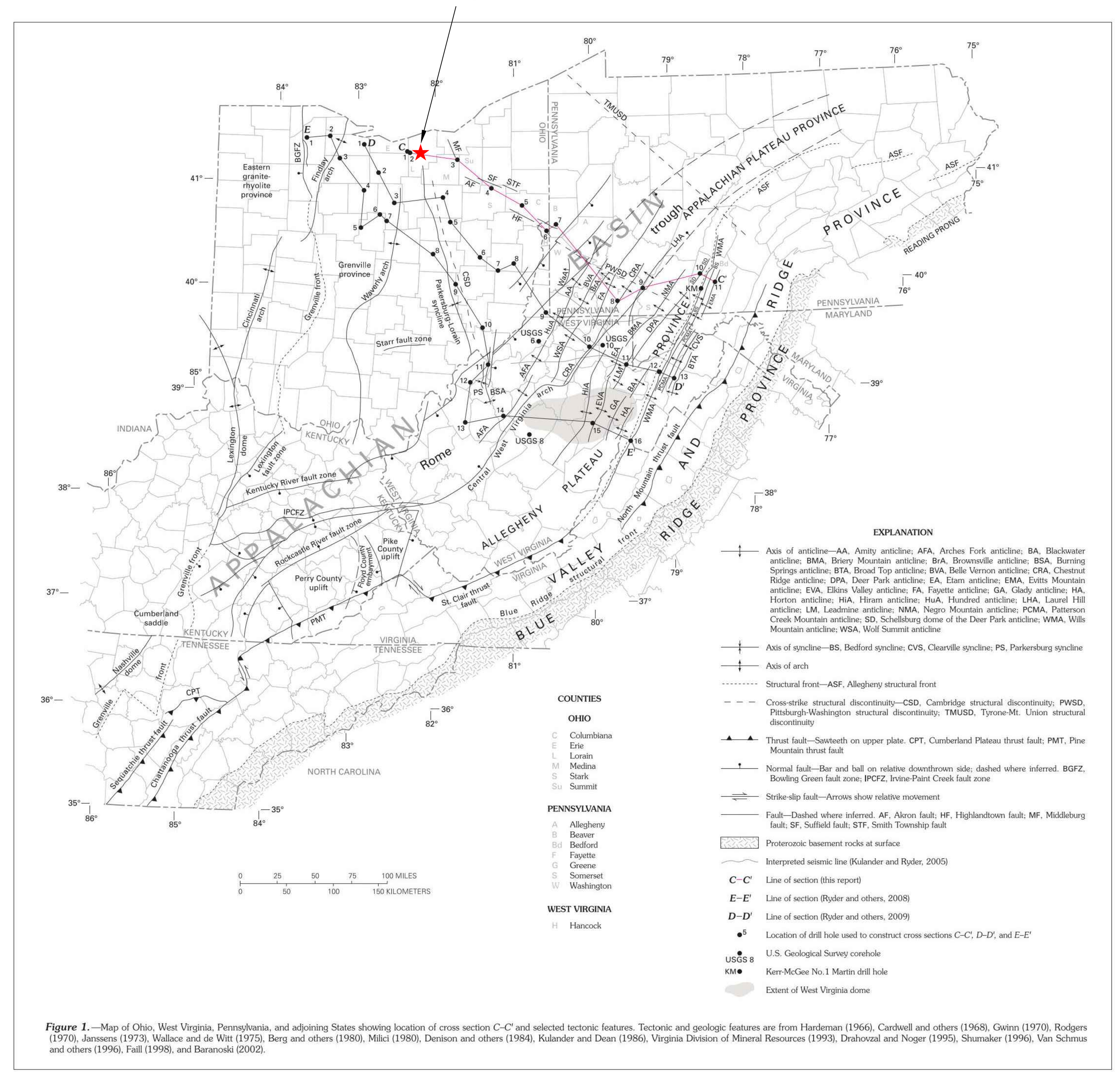


Figure 1.—Map of Ohio, West Virginia, Pennsylvania, and adjoining States showing location of cross section C–C' and selected tectonic features. Tectonic and geologic features are from Hardeman (1966), Cardwell and others (1968), Gwinn (1970), Rodgers (1970), Janssens (1973), Wallace and de Witt (1975), Berg and others (1980), Milici (1980), Denison and others (1984), Kulander and Dean (1986), Virginia Division of Mineral Resources (1993), Drahovzal and Noger (1995), Shumaker (1996), Van Schmus and others (1996), Faill (1998), and Baranoski (2002).

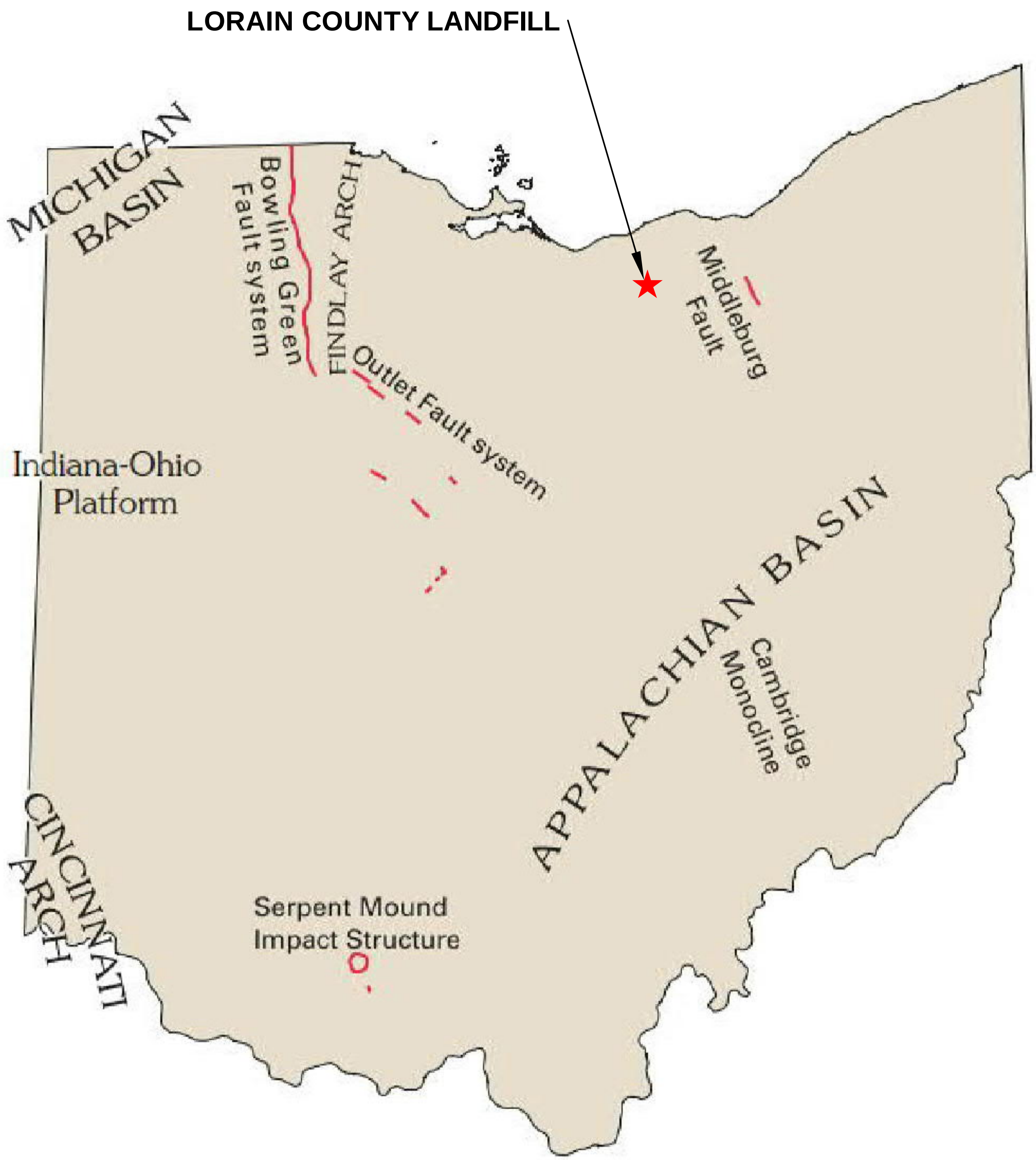
GEOLOGIC CROSS SECTION C–C' THROUGH THE APPALACHIAN BASIN FROM ERIE COUNTY, NORTH-CENTRAL OHIO, TO THE VALLEY AND RIDGE PROVINCE, BEDFORD COUNTY, SOUTH-CENTRAL PENNSYLVANIA

FIGURE 2-8

By
Robert T. Ryder, Michael H. Trippi, Christopher S. Swezey, Robert D. Crangle, Jr., Rebecca S. Hope, Elisabeth L. Rowan, and Erika E. Lentz

2012

For sale by U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225; telephone 1-888-ASK-USGS
Printed on recycled paper
ISBN 978-1-4113-3277-5



Source: Slucher et al, 2006

WSP USA Inc.
16200 Park Row, Ste. 200
Houston, TX 77084
TEL: (281) 589-5900

LORAIN CARBON ZERO SOLUTIONS, LLC
LORAIN COUNTY, OHIO

REGIONAL STRUCTURAL FEATURES IN OHIO	Job No. 192128N

Drawn: WDD	Checked: MEC	Approved: GEM	Date: 03/01/2021	Scale: NONE	Figure No. 2–9

Sensitive, Confidential, or Privileged Information

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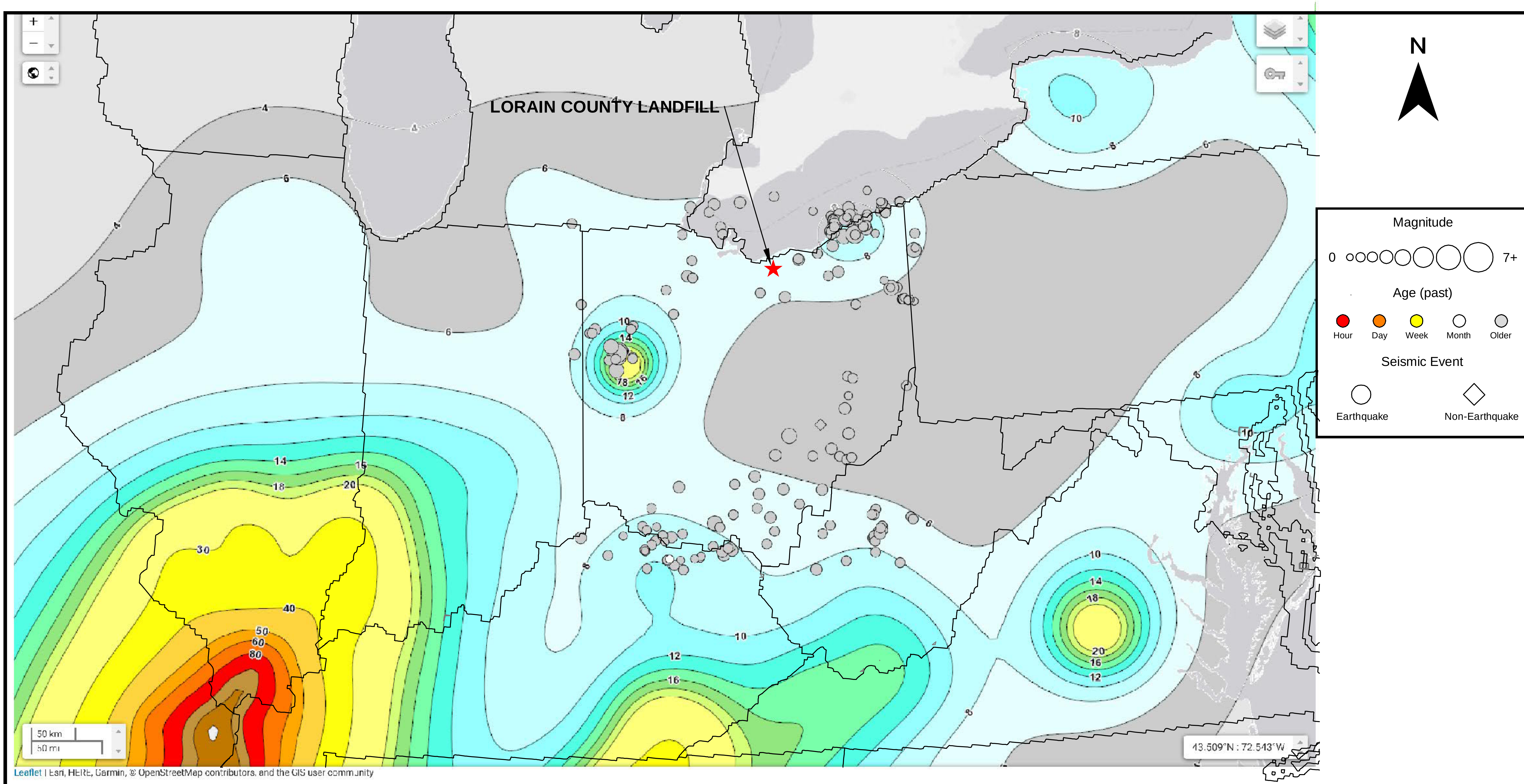

https://earthquake.usgs.gov/earthquakes/map/?extent=36.45664,-92.20825&extent=43.88998,-71.1145&range=search&showPlateBoundaries=false&showUSHazard=true&timeZone=utc&list=false&search=%7B"name":"Search Results","params":%7B"starttime":"1900-01-01 00:00:00","maxlatitude":42.098,"minlatitude":38.... 1/1

* See https://www.sec.gov/Archives/edgar/data/1060391/000106039120000016/exhibit211-subsidiarie.htm for listing of Republic subsidiaries and affiliates

wsp — WSP USA Inc. 16200 Park Row Ste. 200 Houston, Texas 77084 TEL: (281) 589-5900	**LORAIN CARBON ZERO SOLUTIONS, LLC** **LORAIN COUNTY, OHIO**
REGIONAL SEISMIC HAZARD MAP	Job No. 192128N

Drawn: WDD	Checked: MEC	Approved: GEM	Date: 03/01/2021	Scale: NONE	Figure No. 2–17

2.7 - Ohio
41.390°N 83.300°W
2010-05-14 02:27:02 (UTC)

2.7 - Ohio
1998-11-25 02:55:06 (UTC)
41.071°N 82.405°W

2.7 - Ohio
2010-05-17 21:29:05 (UTC)
41.240°N 81.510°W

2.1 - 1km ESE of North Olmsted, Ohio
2014-01-20 06:50:18 (UTC)
41.408°N 81.906°W

2.0 - 1km NE of Newburgh Heights, Ohio
2019-03-06 04:15:03 (UTC)
41.459°N 81.653°W

3.0 - Ohio
1974-09-29 02:26:17 (UTC)
41.238°N 83.361°W

3.0 - Ohio
2011-06-05 15:35:21 (UTC)
41.030°N 82.080°W

3.7 - Ohio2.1 - 1km ESE of North Olmsted, Ohio
2014-01-20 06:50:18 (UTC)
41.408°N 81.906°W
2007-03-12 23:18:16 (UTC)
41.280°N 81.380°W

3.4 - Cleveland urban area, Ohio
1900-04-09 14:00:00 (UTC)
41.400°N 81.900°W

3.4 - Cleveland urban area, Ohio
1991-01-26 03:21:22 (UTC)
41.536°N 81.453°W

2.4 - Ohio
2010-02-25 22:13:12 (UTC)
41.220°N 83.290°W

2.9 - Ohio
2000-08-07 02:02:30 (UTC)
40.958°N 81.151°W

Source: USGS Earthquake Hazards Program, Earthquake Catalog, https://earthquake.usgs.gov/earthquakes/search

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SEISMICITY IN THE VICINITY OF THE SITE

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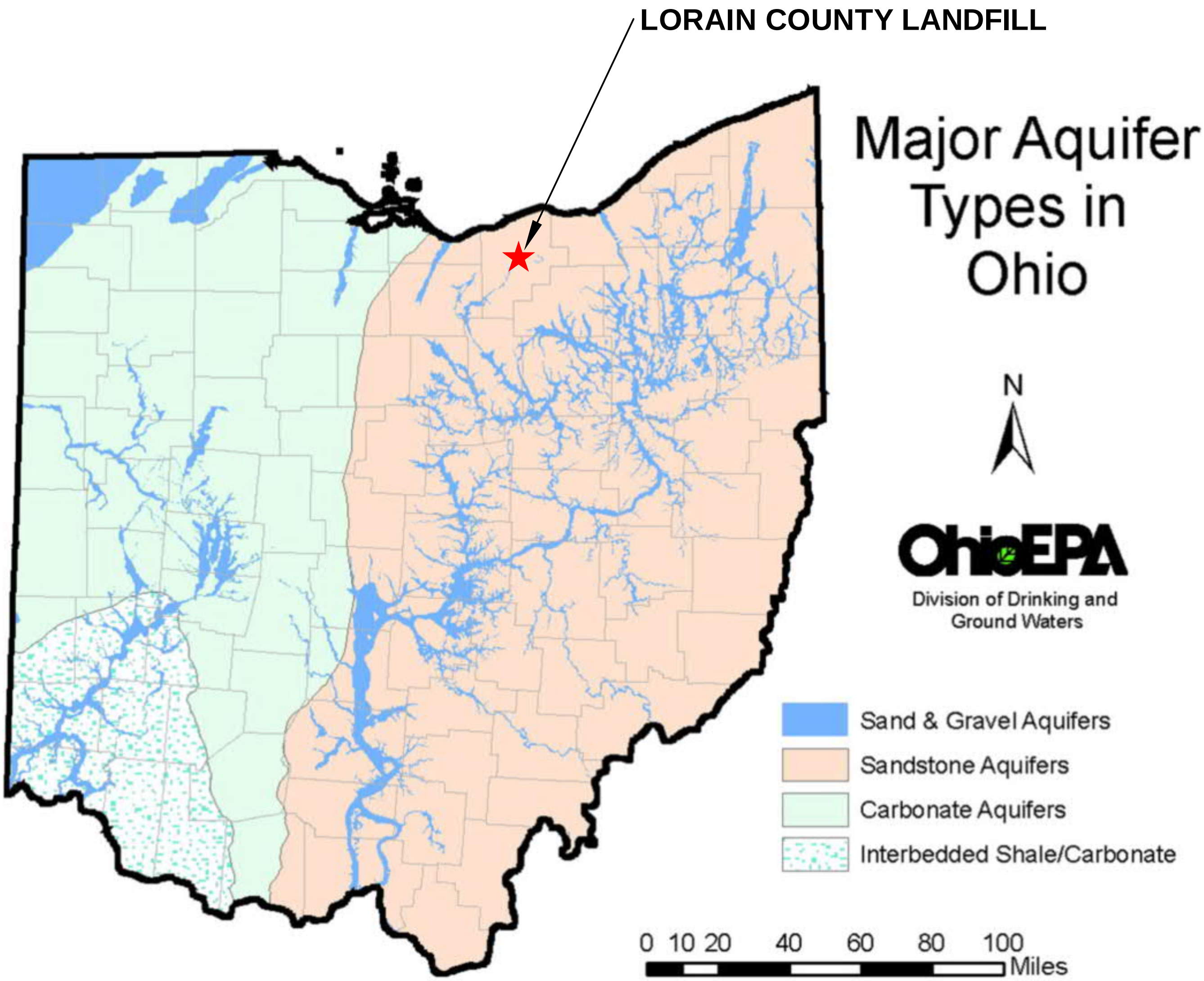


Figure 1. Distribution of major aquifers in Ohio, modified from ODNR Aquifer Maps (Ohio EPA, 2000).

Source: ODNR, 2000

WSP USA Inc. 16200 Park Row, Ste. 200 Houston, TX 77084 TEL: (281) 589-5900		LORAIN CARBON ZERO SOLUTIONS, LLC LORAIN COUNTY, OHIO		
MAJOR AQUIFER TYPES IN OHIO				Job No. 192128N
Drawn: WDD	Checked: MEC	Approved: GEM	Date: 03/01/2021	Scale: NONE · Figure No. 2–19

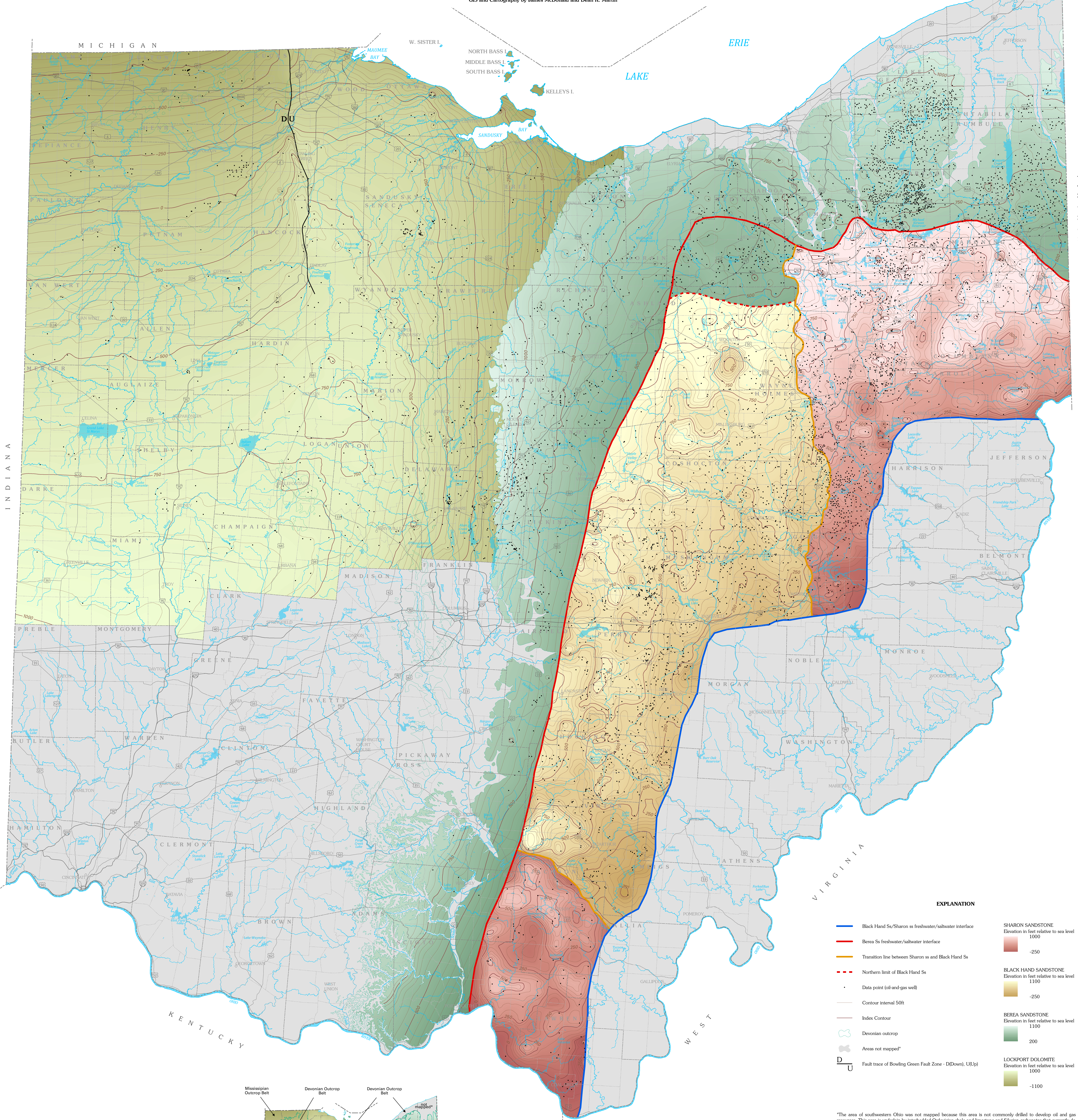
STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Thomas J. Serenko, Chief

ELEVATION CONTOURS ON THE BASE OF THE DEEPEST UNDERGROUND SOURCES OF DRINKING WATER IN OHIO

by
Ronald A. Riley

GIS and Cartography by James McDonald and Dean R. Martin

MAP EG-6
Funded, in part, by the U.S. EPA
through the Ohio EPA Nonpoint Source Program, Section 319
9/2012



EXPLANATION

(blue line)	Black Hand Ss/Sharon ss freshwater/saltwater interface
(red line)	Berea Ss freshwater/saltwater interface
(orange line)	Transition line between Sharon ss and Black Hand Ss
(red dashed line)	Northern limit of Black Hand Ss
•	Data point (oil-and-gas well)
(thin line)	Contour interval 50ft
(dark line)	Index Contour
(green outline)	Devonian outcrop
(gray fill)	Areas not mapped*
D / U	Fault trace of Bowling Green Fault Zone - D(Down), U(Up)

SHARON SANDSTONE
Elevation in feet relative to sea level
1000
-250

BLACK HAND SANDSTONE
Elevation in feet relative to sea level
1100
-250

BEREA SANDSTONE
Elevation in feet relative to sea level
1100
200

LOCKPORT DOLOMITE
Elevation in feet relative to sea level
1000
-1100

*The area of southwestern Ohio was not mapped because this area is not commonly drilled to develop oil and gas resources. This area is underlain by interbedded Ordovician shale and limestone and Silurian carbonates that currently do not contain commercial quantities of oil or natural gas. Most groundwater sources in this area are within relatively shallow glacial outwash deposits and recent alluvial sediments.

The area of southeastern Ohio is underlain primarily by sandstone, shale, coal, and freshwater limestone of Mississippian and Pennsylvanian ages. The lenticular, braided, intertwining nature of these deposits prohibits reliably naming and mapping a lowest USDW across any appreciable portions of this area. Casing depths in this area are set on a various USDWs.

The shaded area in extreme northeastern Ohio, bordering Lake Erie, also was not mapped. In this area, the top of bedrock is the Devonian-age Ohio Shale and yields small quantities of water locally from weathered and fractured zones in Devonian and Mississippian shales. Potable water is primarily from the overlying glacial deposits.

N

10 5 0 10 20 30 40 Miles

10 5 0 10 20 30 40 50 Kilometers

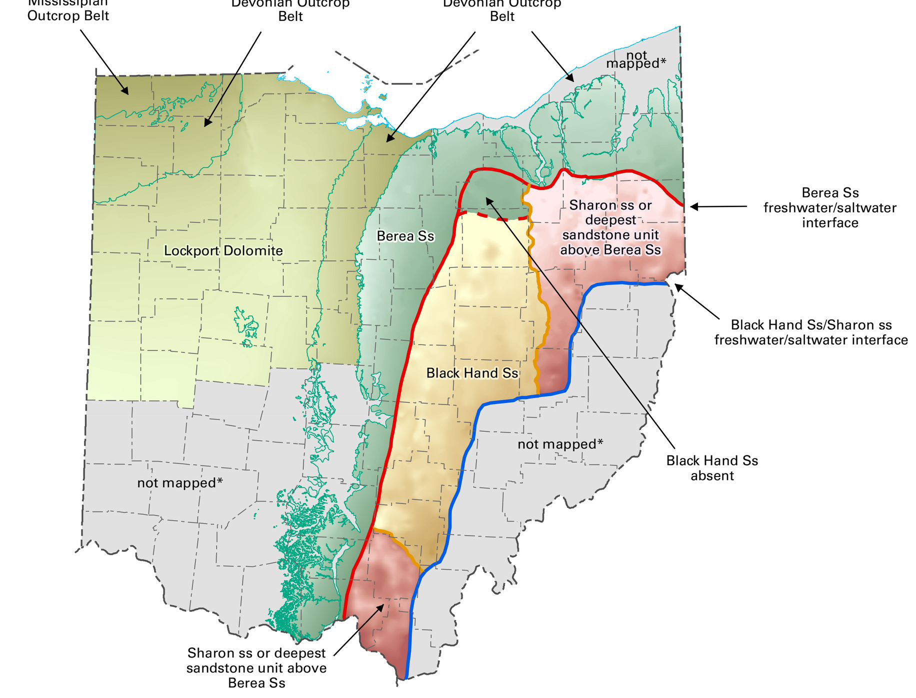
SCALE 1:500 000

Base map derived from Ohio Department of Transportation data sets.
Projection of data is Ohio coordinate system, south zone, North American Datum, 1983.

MAPPING CONVENTIONS

The deepest underground source of drinking water (USDW) in northwestern Ohio is defined by Sedam and Stein (1970) and other published reports as the Lockport Dolomite (Silurian) except within the Devonian and Mississippian outcrop belts, where the deepest USDW may be the Lower and Middle Devonian/Upper Silurian carbonates or the Devonian and Mississippian shales. For continuity of mapping, the base of the Lockport Dolomite was mapped throughout northwestern Ohio. The deepest USDW and freshwater/saltwater interface (using 10,000 ppm total dissolved solids) in eastern Ohio is based on Vogel (1982). Southwestern Ohio lies outside the major petroleum-producing areas of the state and its deepest USDW is not mapped. The deepest USDW also was not mapped in southeastern Ohio because the complex stratigraphic nature of these deposits prohibits reliably naming and mapping a lowest USDW across the area.

This map is modified from Riley (2001). Elevations are relative to mean sea level at the base of each mapped unit; contour interval is 50 feet.



Index map of project area showing USDW mapped units.

REFERENCES

Riley, R.A., 2001, Mapping the deepest underground sources of drinking water in Ohio: Columbus, Ohio Department of Natural Resources, Division of Geological Survey final report to U.S. EPA on 319(h) grant, 5 p., 1 map (scale 1:500,000).

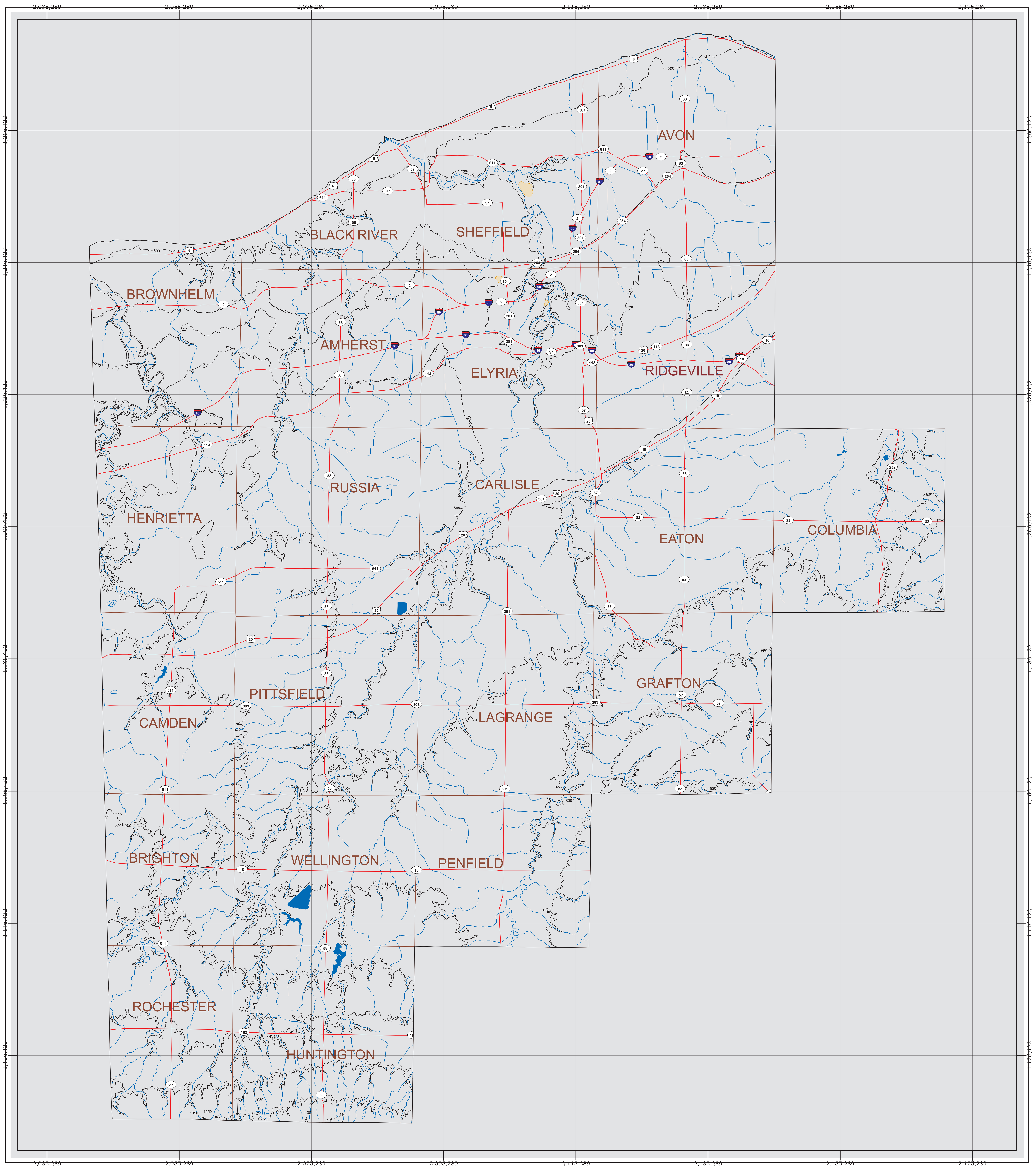
Sedam, A.C. and Stein, R.B., 1970, Saline ground-water resources of Ohio: U.S. Geological Survey Hydrologic Investigations Atlas HA-366, 2 sheets.

Vogel, D.A., 1982, Salt/fresh water interface, ground-water mapping project—Final report to U.I.C. Program: Columbus, Ohio Department of Natural Resources, Division of Water, 15 p., 11 fig., 33 data tables.

Recommended bibliographic citation:

Riley, R.A., with GIS and cartography by McDonald, James, and Martin, D.R., 2012, Elevation contours on the base of the deepest underground sources of drinking water in Ohio: Columbus, Ohio Department of Natural Resources, Division of Geological Survey, Map EG-6, scale 1:500,000.

FIGURE 2-20



Potentiometric Surface of the Consolidated Aquifers in Lorain County

by
Kathy Sprowls
Ohio Department of Natural Resources
Division of Water

This map shows the elevation of the ground water level that was measured from individual water wells completed in the consolidated (bedrock) aquifers within Lorain County.

Ground water potentiometric surface (water level) maps indicate the elevation and general direction of ground water flow. Ground water flows from areas of higher head elevations to lower head elevations in a direction perpendicular to the contour lines. This map only depicts the horizontal gradient.

These maps could be used to determine ground water recharge and discharge areas, as input data into ground water modeling programs, and to locate monitoring wells in the correct locations to satisfy compliance monitoring. These maps could also be used to assist in preparing water resource plans, to assist in preparing technical studies, the mapping of stress areas, and in possible ground water diversion issues. Since these maps were created from existing data collected over a fifty-year period, field verification of the ground water flow direction should be conducted before any site specific work is conducted.

Legend

- 800 Ground Water Elevation, in feet
- Roads
- Streams
- Lakes
- Townships
- No Aquifer / No Data--Local areas containing deep quarries

Contour interval is 50 feet. Contour elevations are measured from Mean Sea Level.

Black grid represents the State Plane South Coordinate System (NAD27, feet).

0 1 2 3 4 5
Miles

0 1 2 4 6 8
Kilometers

Disclaimer

This map was created using static water level readings from water well records collected over a 50 (+/-) year period. The Division of Water was technically reviewed this map but disclaims any responsibility or liability for interpretations or decisions based thereon. In no event shall the Division of Water have any liability whatsoever for payment of any kind, including but not limited to, any loss of profits arising out of use of or reliance on the maps.

Ohio Department of Natural Resources
Division of Water
Ground Water Resources Section
1939 Fountain Square
Columbus Ohio 43224
www.dnr.state.oh.us
March 2005

FIGURE 2-21

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APPENDIX

2-1 ISOPACH MAP OF THE EAU CLAIRE FORMATION

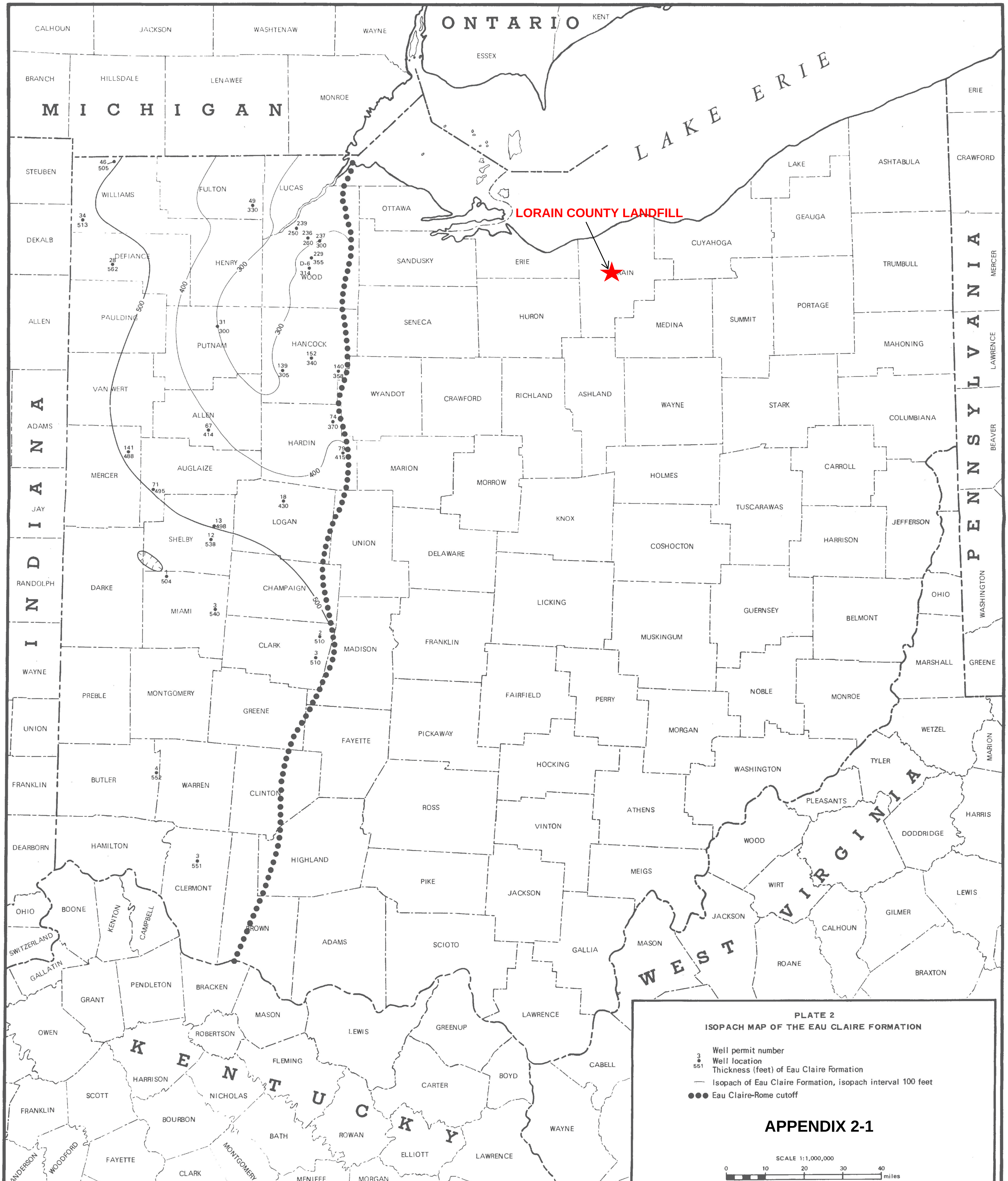
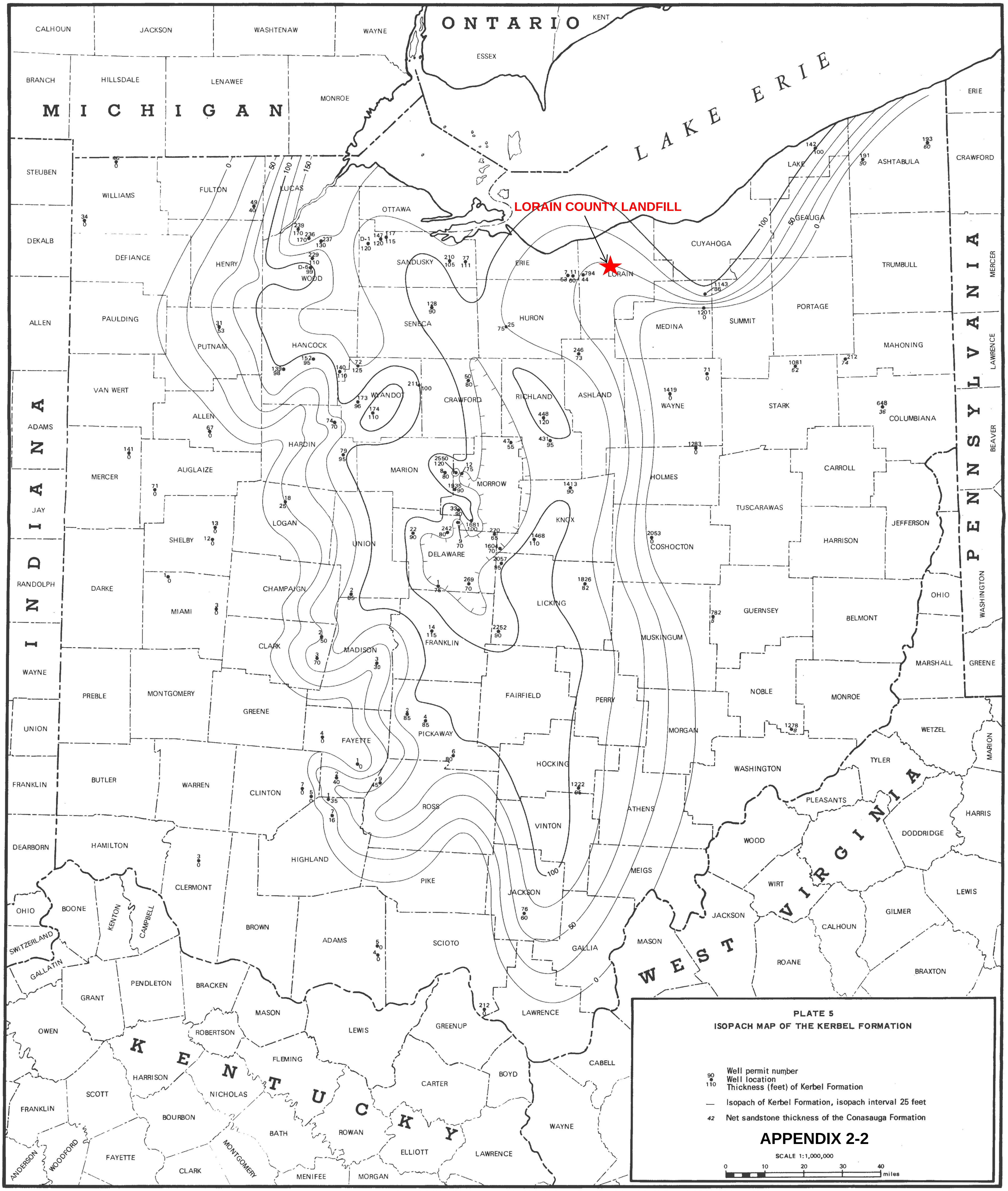


PLATE 2
ISOPACH MAP OF THE EAU CLAIRE FORMATION

APPENDIX 2-1

APPENDIX

2-2 ISOPACH MAP OF THE KERBEL FORMATION


LORAIN COUNTY LANDFILL
ONTARIO
LAKE ERIE
MICHIGAN
INDIANA
PENNSYLVANIA
WEST VIRGINIA
KENTUCKY
PLATE 5
ISOPACH MAP OF THE KERBEL FORMATION
90 110 Well permit number
Well location
Thickness (feet) of Kerbel Formation
Isopach of Kerbel Formation, isopach interval 25 feet
42 Net sandstone thickness of the Conasauga Formation
APPENDIX 2-2
SCALE 1:1,000,000
0 10 20 30 40 miles

APPENDIX

3-1 REPUBLIC CLASS VI WELL PERMIT CCS RESERVOIR SIMULATION

LORAIN CLASS VI WELL PERMIT CCS RESERVOIR SIMULATION

LORAIN COUNTY OHIO

TOPICAL REPORT RSI-3150

PREPARED BY
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Yannick Champollion

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PREPARED FOR
WSP USA
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JULY 2021

Project Number 4213

RESPEC

EXECUTIVE SUMMARY

The primary objective of this reservoir study was to determine the feasibility of injecting 120,000 t/year super critical carbon dioxide (sCO2) into the Mt Simon Formation at the Lorain County Landfill. Model results indicate that a single vertical well would not provide the required injection capacity, but that two vertical/deviated wells with sufficient separation or a single 1200m long horizontal well would suffice. The Area of Review distance calculated from the 3D model is 5000m around the horizontal well based on the maximum acceptable pressure increase; however, the sCO2 plume would only travel 1000m away from the horizontal well after 30 years of operations. Finally, the Rome formations act as a suitable confining unit to keep the injection sCO2 within the Mt Simon formation.

Reservoir simulation was done using TOUGH3 developed and licensed by Lawrence Berkeley National Lab. Reservoir model parameters were based on downhole geophysical logs and published values in literature. Multiple well designs were investigated including horizontal and vertical/deviated wells. Reservoir simulations were run to generate key performance metrics, reservoir pressure and CO2 saturations with target output times of 5, 12 and 30 years. Simulations resulted in a final base case design of a single 1200m long horizontal well located within the footprint of Lorain's land ownership to meet the specified target flow rate and maintain the reservoir pressures below fracking pressure. A sensitivity study was done varying reservoir parameters to understand the impacts of reservoir quality and uncertainty to the overall system performance.

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RESPEC

v

RSI-4213

1.0 INTRODUCTION

A reservoir feasibility study was conducted by RESPEC to determine the viability of injecting 120,000 t/year of super critical carbon dioxide (sCO2) into the Mt Simon Formation at the Lorain County landfill (Ohio). The objectives of the reservoir study were as follows:

- Demonstrate the feasibility of injecting 120,000 t/year of sCO2 into the Mt Simon Formation at the Lorain County landfill.
- Evaluate the feasibility of using vertical/deviated well(s) vs. horizontal well(s)
- Calculate the Area of Review distances based on the US Environmental Protection Agency 2013 guidance (EPA 2013).
- Verify that the maximum predicted reservoir pressure remains below fracking pressure and that the injected sCO2 remains trapped within the Mt Simon reservoir.
- Conduct a sensitivity study to understand well field operations and risks within a reasonable range of predicted reservoir parameters.

Downhole geophysical logs, isopach and structure maps provided by WSP, and literature values were used to build numerical reservoir models of the Mt Simon reservoir and overlying Rome/Conasauga confining units. Reservoir simulation was done using TOUGH3 with the ECO2M equation of state (EOS) developed and licensed by Lawrence Berkeley National Lab. The TOUGH family of codes has been a primary geothermal and CO_2 reservoir simulator used internationally since the 1980's. ECO2M is a fluid-property module for the TOUGH3 simulator (Version 2.0) that was designed for applying to the geologic storage of CO_2 in saline aquifers. The ECO2M EOS includes a comprehensive description of the thermodynamics and thermophysical properties of H_2O–NaCl–CO_2 mixtures. The EOS reproduces fluid properties largely within experimental error for temperature (T), pressure (P), and salinity conditions in the range of 10 degrees Celsius (°C) ≤ T ≥ 110°C, P ≤ 600 bar. The fluid salinity can range from 0 to 100 percent halite saturation. ECO2M can describe all of the possible phase conditions for brine-CO_2 mixtures, including transitions between super and subcritical conditions and phase changes between liquid and gaseous CO_2. This report documents the methodology, results and conclusions from the feasibility study.

2.0 RESERVOIR PROPERTIES

2.1 GEOLOGICAL MAPS

Isopach and structure maps were provided by WSP for the Mt Simon reservoir and the Rome Formation caprock in the Geology section of the WSP report. The maps were used to construct the model geometry. The figures referenced in the WSP report are as follows:

- Figure 2-13 Structure Map Of The Top Of The Confining Zone (Conasagua Formation)
- Figure 2-14 Isopach Map Of The Confining Zone (Conasagua And Rome Formations)
- Figure 2-15 Structure Map Of The Top Of The Injection Zone (Mt. Simon Sandstone)
- Figure 2-16 Isopach Map Of The Injection Zone (Mt. Simon Sandstone)

2.2 POROSITY AND PERMEABILITY

Porosity and permeability are two of most important parameters that define the ability of fluid to be stored and move through a rock. Porosity is the void space between grains or fractures divided by the total volume of a reservoir expressed as a percentage. Permeability is ability of fluid to flow through the pore space. Permeability is often expressed in dimensionless units called a Darcy, named after the famous hydrogeologist Henry Darcy. The thickness of the reservoir multiplied by the permeability (meter x Darcy), called Transmissivity, is the most important factor when describing the reservoir and its ability to produce and inject fluid. Permeability can measure directly through lab tests on core or indirectly through flow tests either in-situ drill stem tests or well tests. Well flow tests either production or injection often are the most accurate in understanding the bulk reservoir properties and transmissibility. Core with downhole geophysical logs can help describe the reservoir properties and distributions.

There are very few penetrations of the Mt. Simon Formation in the study area, none were cored. The closest well to the Lorain landfill is located >10km away. Six well bores deep enough to intersect some or all geological formations being modelled for CCS were available within the Ohio Basin. All 6 logs were used to confirm formation elevations and identify regional correlative geological zones and horizons for the Mt Simon Sandstone and Rome Formation. Detailed geophysical log analysis was carried out on three of the wells (ID # 20011, 20907, 21819) that contained adequate geophysical wireline-log data to evaluate potential effective porosity and estimate permeability. Porosity values were determined for prospective horizons using standard petrophysical methods. Because core and actual core data was not available, permeabilities were estimated using a porosity-permeability relationship retrieved from studies carried out on Lower Ordovician rocks in Ohio by [Janssens,1973] and from [FutureGen 2013] that included the Mount Simon Sandstone in the Illinois Basin. These studies indicate that permeability values of Mount Simon (and related siliciclastic rocks) are primarily a function of porosity. For this report, it is assumed that the Paleozoic basins in Illinois and in Ohio have reasonably similar geological depositional histories for the Mount Simon Sandstone, and overlying cap rock.

Well 21819 was used as a reference well for the study area to define geologic subunits within the Mt Simon, Rome and Conasauga formations, as well as their relative thicknesses and reservoir properties. The petrophysical log for Well 21819 is shown on Figure 2-1 and the geologic subunits and associated reservoir properties are presented on Figure 2-2

21819 - PreView

Sensitive, Confidential, or Privileged Information

[redacted]

Figure 2-1 Petrophysical Logs for Well 21819

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[redacted]

Figure 2-2 Reservoir properties and geologic subunits for Well 21819

2.3 FLUID AND GAS

There are no water samples available from the Mt Simon Formation in the study area. The Total Dissolved Solids (TDS) concentrations in the Mt Simon Fm at the Lorain site are estimated at 50,000 mg/L (Table 2.16, p.2.46 of the [FutureGen Industrial Alliance, 2013]).

No free gas was noted in the reservoir on geophysical logs and therefore no free gas component is modeled in the system. The reservoir simulation is initialized with 0% gas saturation.

2.4 RELATIVE PERMEABILITY

Since site-specific relative permeability data does not exist, the following relative permeability curves brine-sCO2 were derived from published literature (Figure 2-3 and Table 2-1) using the Van Genuchten model.

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[redacted]

The relative permeability curves described just above were used for all simulations using the 3D model except where noted. The ‘default’ relative permeability curves (Table 2-1) described in the ECO2M manual (Pruess 2013) were used for all runs using the 2D model and for one sensitivity run using the 3D model.

2.5 CAPILLARY PRESSURE

Since site-specific capillary pressure data does not exist, the following capillary pressure curves were derived from published literature (Figure 2-4 and Table 2-2) using the Van Genuchten model.

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[redacted]

Table 2-2 Capillary Pressure parameters for the Mt Simon and Rome formations

The capillary pressure curves described just above were used for all simulations using the 3D model except where noted. The 'default' capillary pressure curves (Table 2-2) described in the ECO2M manual (Pruess 2013) were used for all runs using the 2D model and for one sensitivity run using the 3D model.

2.6 EPA MAXIMUM ALLOWABLE PRESSURE

2.6.1 USDW INITIAL PRESSURE

In the study area, the lowermost US drinking water aquifer (USDW) is the Berea Sandstone, with an elevation z_u of 198m ASL at the Lorain site (800' ASL ground elevation and 150' BGL depth based on regional geologic cross-sections and published maps). Using 1000 kg/m3 (freshwater aquifer) and a groundwater elevation of 750' ASL (Ohio groundwater state map WGWPS-10 https://ohiodnr.gov/wps/portal/gov/odnr/discover-and-learn/safety-conservation/about-odnr/geologic-survey/publications-maps/publications-catalog), the initial pressure in the USDW *Pu* is 300 kPa.

2.6.2 MT SIMON INITIAL PRESSURE

At the Lorain site, the Mt Simon reservoir elevation z_i is estimated at -1,228m ASL. Using a brine density of 1025 kg/m3 and a hydraulic head of 75m ASL based on literature (Fig 1 p. B5 of 23 [Archer Daniels Midland, 2016]), the initial pressure in the Mt Simon reservoir is calculated at 13.11 MPa.

2.6.3 EPA MAXIMUM ALLOWABLE PRESSURE

The EPA maximum allowable pressure for the project was calculated as per the US EPA Method 1 (under-pressurized case) described in the US EPA 2013 guideline for the Geologic Sequestration of Carbon Dioxide [EPA 2013]. This guideline defines the pressure-front $P_{i,f}$ as "the area around an injection well where, during injection, the [hydraulic] head of the formation fluid in the injection zone is equal to or greater than the [hydraulic] head of USDWs." Defined this way, the pressure-front may be calculated by the following equation:

$$Pi,f = Pu + \rho ig \text{ x } (zu - zi)$$

where Pu is the initial fluid pressure in the USDW, ρi is the injection-zone fluid density, g is the acceleration due to gravity, z_u is the representative elevation of the USDW, and z_i is the representative elevation of the injection zone.

Similarly, the increase in pressure that may be sustained in the injection zone (ΔPi,f) is:

$$\Delta Pif = Pu + \rho ig \text{ x } (zu - zi) - Pi$$

Based on the equation and other data above, the pressure front $P_{i,f}$ is estimated at 14.64 MPa and the threshold pressure change used for the AOR is calculated at 1.54 MPa.

2.7 MAXIMUM OPERATING PRESSURE

The maximum sand face (reservoir) injection pressure must remain well below the frac pressure of the caprock such that the caprock retains its sealing capacity during operations. To calculate the maximum injection pressure (MOP), a fracture gradient of 0.65 psi/ft (14.7 kPa/m) was used based on literature review.

As the minimum depth to the top of the reservoir is 1442.5 m BGL in the area above the injection well, the MOP is calculated as follows:

MOP = 1442.5 m BGL x 14.7 kPa/m x 90% safety factor = 19.1 MPa.

Given the initial reservoir pressure of 13.1 MPa (Section 2.5), the pressure buildup in the reservoir due to injection must remain less than 6.0 MPa during operations to prevent fracking of the caprock.

3.0 NUMERICAL MODELING

Reservoir simulations were run to generate key performance metrics, reservoir pressures and sCO_2 saturations, with target output times of 5, 12 and 30 years. Two separate numerical simulation models were built to efficiently meet the feasibility study objectives. A two-dimensional (2D) radial simulation was constructed for initial well design and investigate model responses. A full well field three-dimensional (3D) model was constructed using actual reservoir geometries to test final well field scenarios derived from the 2D model. Vertical/deviated well(s) and horizontal well(s) were investigated to determine the optimal injection configuration.

3.1 MODELING PLATFORM & THEORY (TOUGH3, ECO2M)

TOUGH3 is a general-purpose numerical simulator for multi-dimensional fluid and heat flows of multiphase, multicomponent fluid mixtures in porous and fractured media. It is developed as an enhanced, more efficient version of the TOUGH2 suite of codes (Jung 2018).

The TOUGH3 simulator is developed for applications involving subsurface flow problems. TOUGH3 solves mass and energy balance equations that describe fluid and heat flow in general multiphase, multicomponent, and multidimensional systems. It fully accounts for the movement of gaseous, aqueous, and non-aqueous phases, the transport of latent and sensible heat, and the transition of components between the available phases, which may appear and disappear depending on the changing thermodynamic state of the system. Advective fluid flow in each phase occurs under pressure, viscous, and gravity forces according to the multiphase extension of Darcy's law, which includes relative permeability and capillary pressure effects. In addition, diffusive mass transport can occur in all phases. The code includes Klinkenberg effects in the gas phase and vapor pressure lowering due to capillary and phase adsorption effects. Heat flow occurs by conduction and convection, as well as radiative heat transfer according to the Stefan-Boltzmann equation. Local equilibrium of all phases is assumed to describe the thermodynamic conditions. TOUGH3 can simulate the injection or production of fluids and heat, including different options for considering wellbore flow effects.

TOUGH3 can simulate various fluid mixtures by means of separate EOS modules, which internally calculate the thermophysical properties of specific fluid mixtures, e.g., fluid density, viscosity, and enthalpy. Due to this flexibility to handle a variety of flow systems, TOUGH3 can be used for diverse application areas, such as geothermal reservoir engineering, geological carbon sequestration, natural gas reservoirs, nuclear waste isolation, environmental assessment and remediation, and flow and transport in variably saturated media and aquifers, among other applications that involve non-isothermal multiphase flows. (Jung, Heng Pau, Finsterle, & Doughty, 2018).

ECO2M is a fluid property module that was designed for applications to geologic storage of CO_2 in saline aquifers. It includes a comprehensive description of the thermodynamics and thermophysical properties of H_2O – NaCl - CO_2 mixtures in the range of 10-110˚C, P <600 bar and salinity up to full halite saturation. Simulations can be isothermal or non-isothermal. ECO2M describes all phase conditions for brine-CO_2 mixtures, including single (aqueous or CO_2-rich) phase, two-phase and three-phase mixtures of aqueous, liquid CO_2 and gaseous CO_2 phases. Fluid phases may appear or disappear in the course of a simulation, and solid salt may precipitate or dissolve. This allows for modeling of CO2 storage and leakage. (Pruess 2013).

3.2 2-D RADIAL MODEL

A simple 2-D radial model was first constructed to quickly evaluate the capacity of the Mt Simon reservoir to store 120,000 t/year of sCO2 and conduct a sensitivity study on plume extent and pressure response to reservoir and fluid properties.

3.2.1 SETUP

The 2D radial model is depicted on Figure 3-1.

- Single model layer representing the Mt Simon reservoir
- The model radius is 100km to allow the dissipation of the pressure changes due tosCO2 injection without edge effects.
- Horizontal discretization: the smallest element is 0.15m at the well and element size grows logarithmically to 9800m at the model edge.
- The model consists of 435 elements.
- No-flow boundaries are assigned on all sides on the model.
- The vertical well is represented by a single source element injecting at a constant rate for the initial 30 years of the simulation and then shut in for the remaining 70 years.

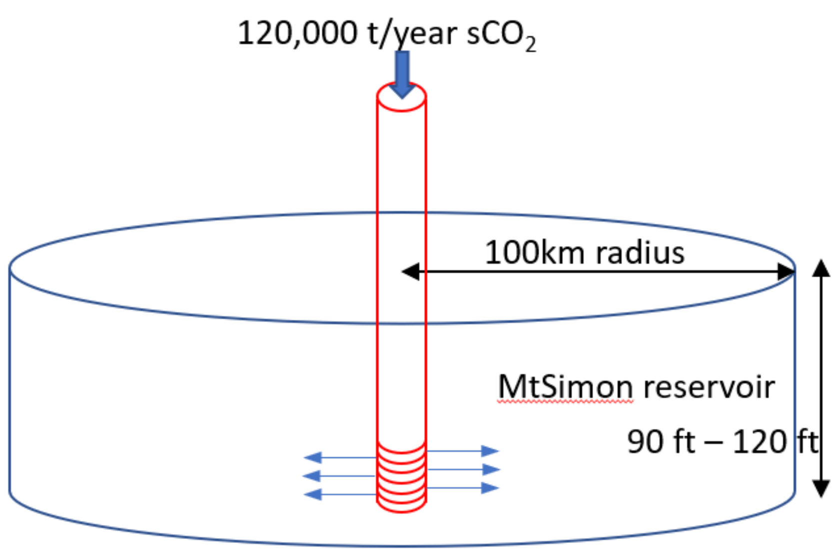

Figure 3-1 2-D Radial Model Conceptual Diagram

3.2.2 INPUTS

The following is a summary of the various model inputs used for the 2D model.

- Rock properties: 9.4mD, 90ft thickness (perm.thickness of 260mD.m), 8.7% porosity.
- Relative permeability and capillary functions are the 'default' functions described in Sections 2.4 and 2.5.
- Initial conditions:
  - 37 °C based on the thermal gradient of 25 °C/km
  - Brine properties (corresponding to 50,000 mg/L TDS): initial salt mass fraction of 0.049% by weight corresponding to a brine density of 1,025 kg/m^3.
  - Initial CO_2 reservoir gas fraction of 0.0

3.2.3 RESULTS

The 2D model was first run with a single vertical well injecting at 120,000 t/year (3.8 kg/s) sCO_2 with the reservoir properties described above. The same model was then run with some properties varied from the base case, Table 3-1. The predicted increase in reservoir pressure is in the order of 7-14 MPa depending on the scenario (Figure 3-2), which exceeds the maximum allowable pressure buildup relative to the MOP (6.0 MPa). These results indicate that a single vertical well injecting at 120,000 t/year sCO_2 for 30 years is not feasible with the assumed reservoir properties. Actual reservoir properties would have to be significantly more favorable than those assumed in terms of thickness and permeability for a single vertical well to be able to meet the project injection requirements.

Table 3-1 Sensitivity Study Parameters

	Base case	Sensitivity
TDS mg/L	[redacted]	[redacted]
rock compressibility m2/N	[redacted]	[redacted]
porosity	[redacted]	[redacted]
initial reservoir T (degC)	[redacted]	[redacted]
reservoir thickness (ft)	[redacted]	[redacted]
intrinsic permeability mD	[redacted]	[redacted]
CO2 injection rate t/yr	[redacted]	[redacted]

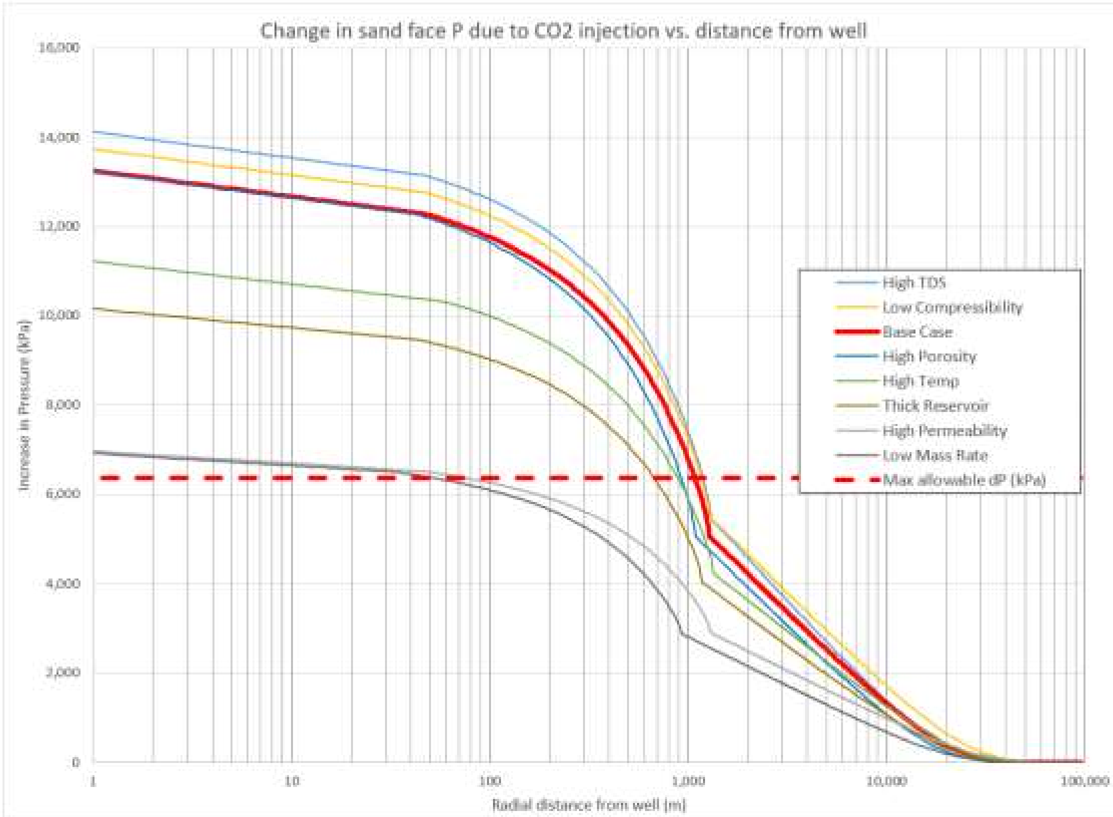

Figure 3-2 Increase in Pressure after 30 years of injection at 120,000 tCO2/year and varied reservoir parameters – 2D model

The 2D model was then ran at half rates (60,000 tCO2/year) and the predicted pressure increase was found to be in the same order as the maximum allowable change in pressure relative to MOP (Figure 3-3). This indicates that the capacity of a single vertical well is in the order of 60,000 tCO2/year for the reservoir properties that were assumed.

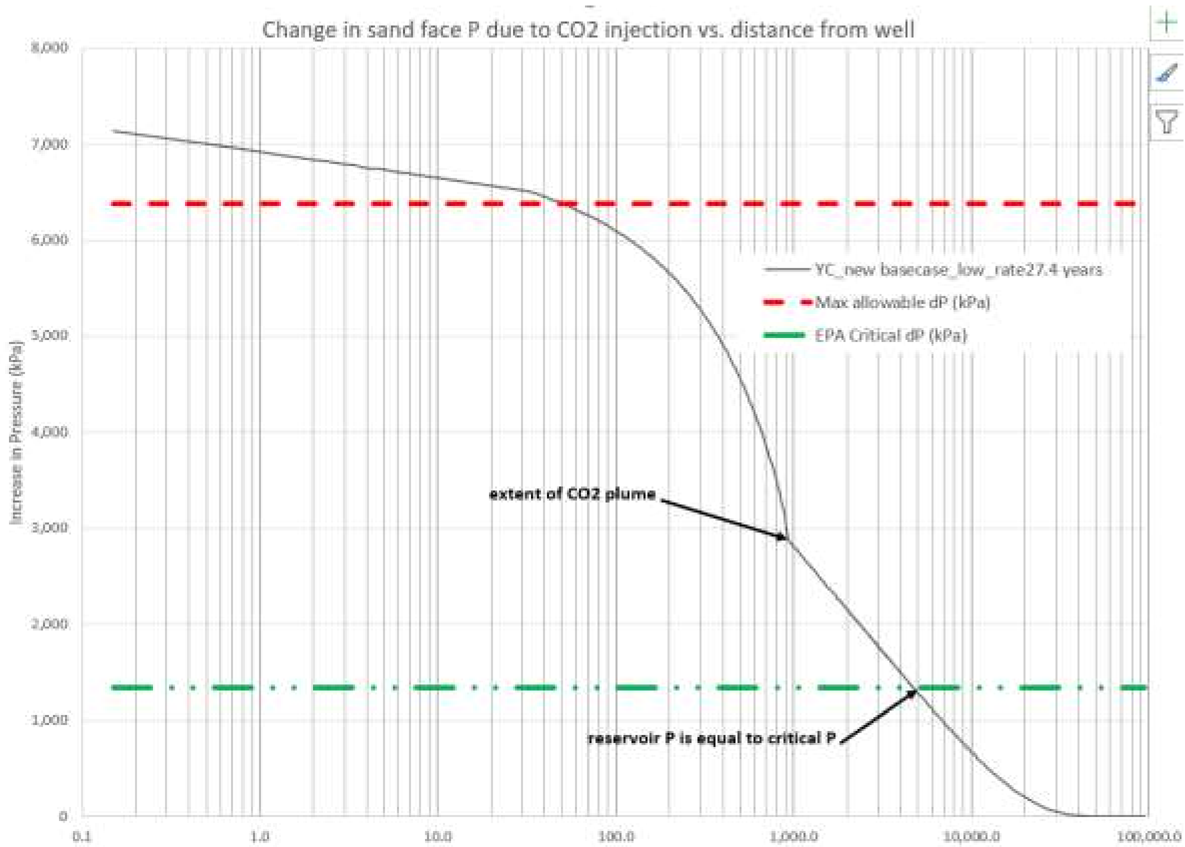

Figure 3-3 Increase in Pressure after 30 years of injection at 60,000 tCO2/year – 2D model

3.3 3-D WELL FIELD MODEL

As explained in the previous sections, the 2D radial model showed that a single vertical/deviated well completed in the Mt Simon reservoir would not have the required injection capacity of 120,000 tCO2/year. A full-field 3D model with a North-South grid was then built to evaluate other development options such as two vertical/deviated wells and horizontal well(s). Once the preferred development option was identified (a single 1200m long horizontal well), the grid for the final simulation was centered over the Lorain landfill site and rotated to align with the direction of the proposed horizontal well.

3.3.1 SETUP

The 3D full field model aims to account for the variability in the geology, 3D interference between the wells and density/temperature related effects. The 3D model grid is depicted on Figures 3-4 to 3-9.

- The model domain is 70km x 70km to allow the dissipation of the pressure changes due to brine production/injection without edge effects. It is centered on the Lorain landfill with a grid rotated 35 degrees clockwise from N (Table 3-2).
- The model grid is hexahedral cartesian, with variable grid elevations based on geologic surfaces derived geologic maps presented in section 2.1. Model element dimensions are between 2.5m and 5000m in the X direction, 2.5m and 5000m in the Y direction and ~1.5m to ~25m in the Z direction.

- The number of nodes vary per layer for a total of 72,708 nodes (Table 3-3)
- Model zones (Table 3-4):
  - The Mt Simon reservoir is subdivided into 4 zones and 6 model layers based on Well 21819. The zone thicknesses vary across the model domain but their relative thicknesses are constant and calculated based on the relative thicknesses at Well 21819. Each reservoir zone is represented by a single model layer, with the exception of the lowermost Mt Simon zone (Mt Simon D) which is subdivided into three model layers due its greater thickness.
  - The Rome Formation constitutes the caprock overlying the Mt Simon reservoir. It is subdivided into three zones of constant relative thicknesses based on Well 21819. The Rome Fm is represented by 9 model layers of variable thicknesses, from very thin just above the Mt Simon reservoir (~2m) to fairly thick (~25m) at the top of the model.
- CO2 injection occurs within model layer1 (second layer from bottom) for horizontal wells and within model layers 0-5 for vertical wells. Injection rates are equally distributed between all the well nodes for the horizontal well(s), with a total of 481 nodes for the 1200m single horizontal well. For vertical wells, injections rates are distributed according to the relative transmissivity of the well nodes in which the well elements are located (smaller rates for nodes with smaller transmissivity).
- No-flow boundaries are assigned on all sides on the model. Constant temperature is achieved at the well nodes by specifying a huge density value for the well nodes.

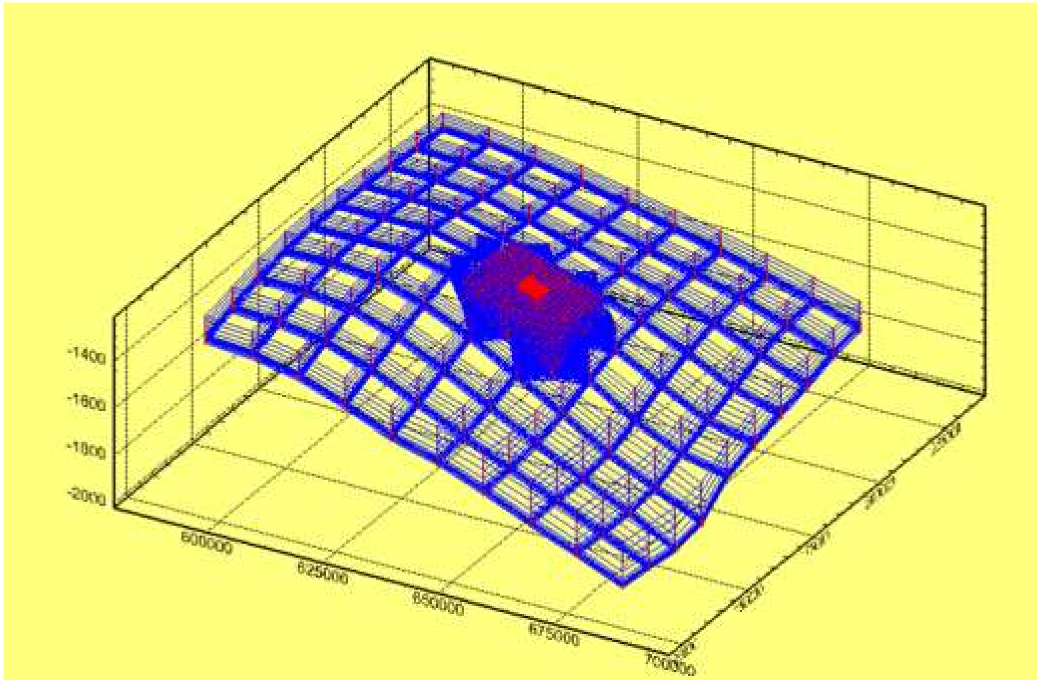

Figure 3-4 Isometric 3D View of 3D Model Grid

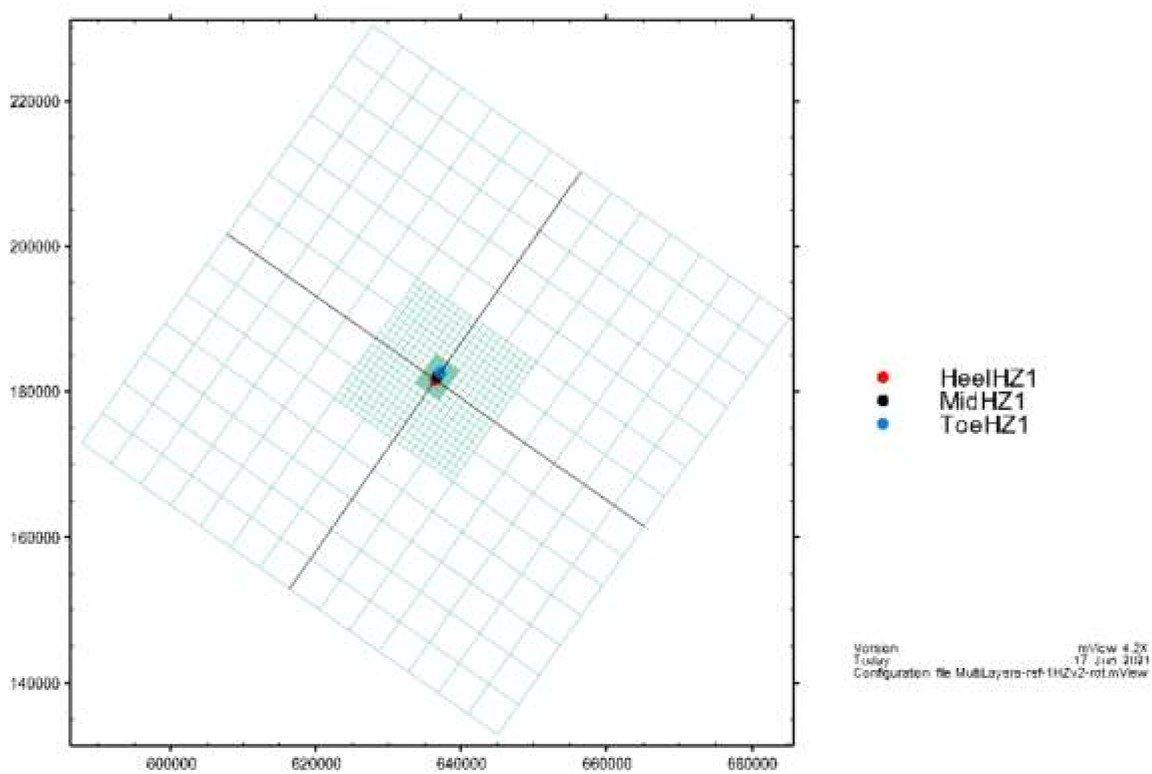

Figure 3-5 model domain – UTM 1927 State Plane of Ohio North

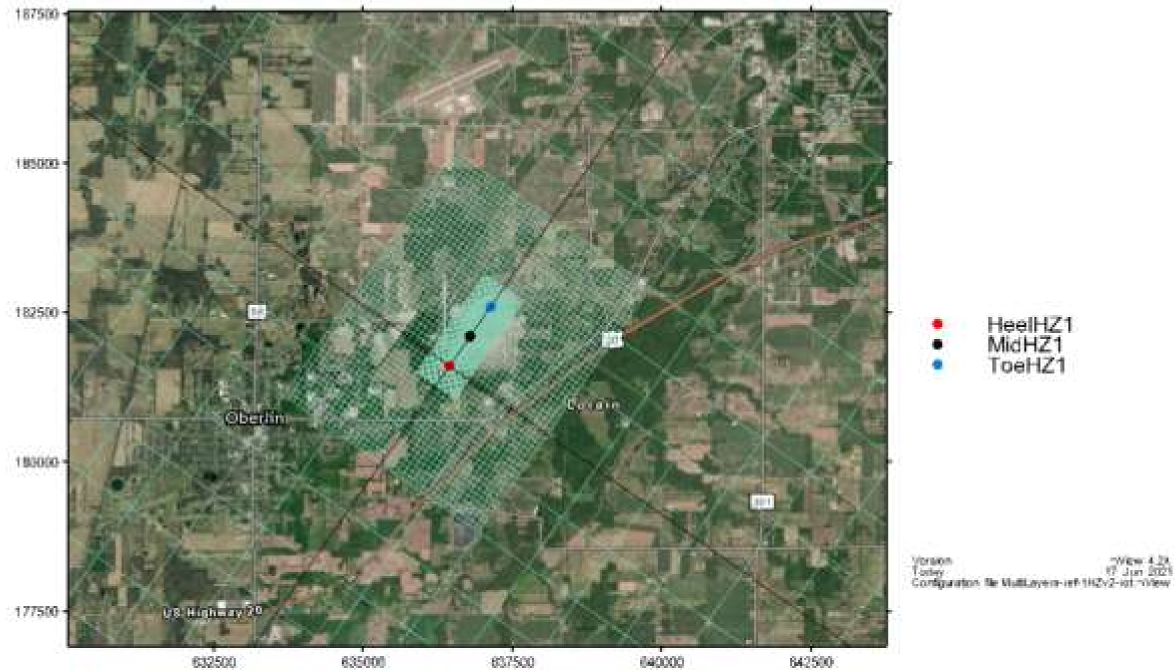

Figure 3-6 model domain overlaid with Google Map air photo – UTM 1927 State Plane of Ohio North

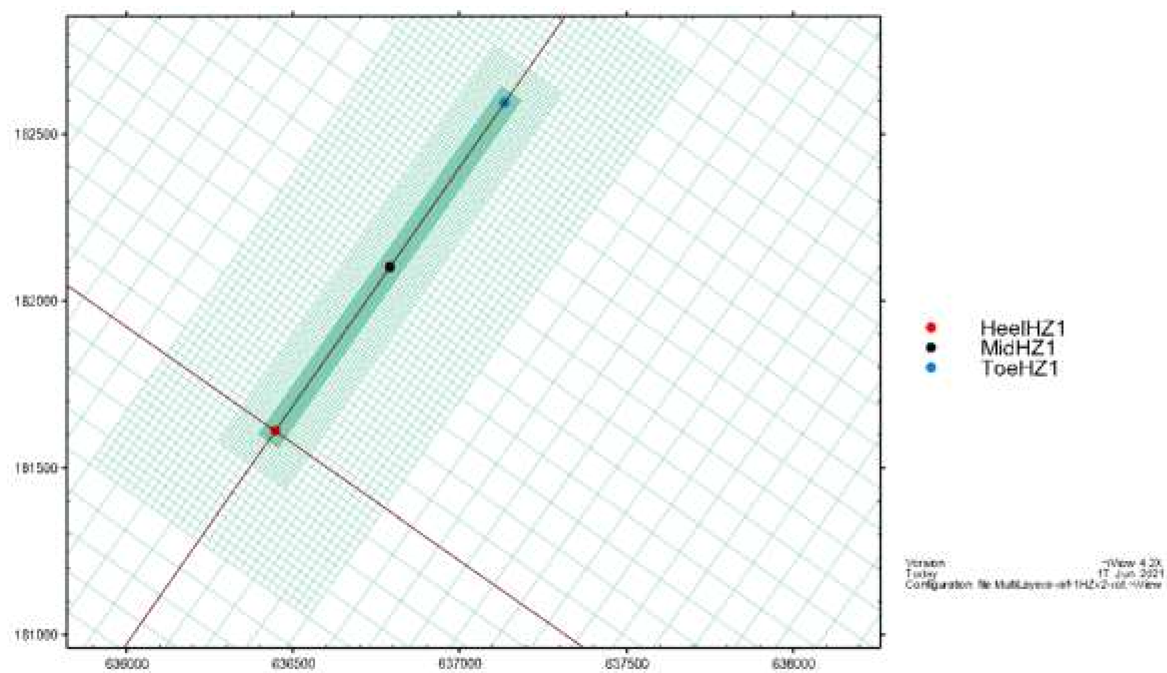

Figure 3-7 model domain zoomed in at the scale of the proposed well – UTM 1927 State Plane of Ohio North

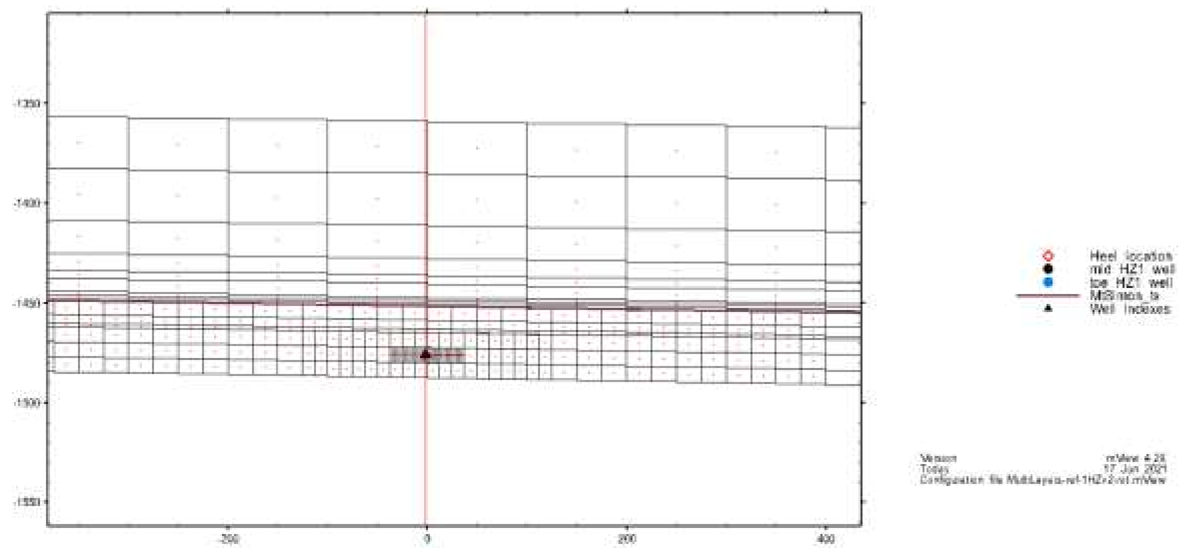

Figure 3-8 Model discretization NW-SE cross-section perpendicular to well – local datum

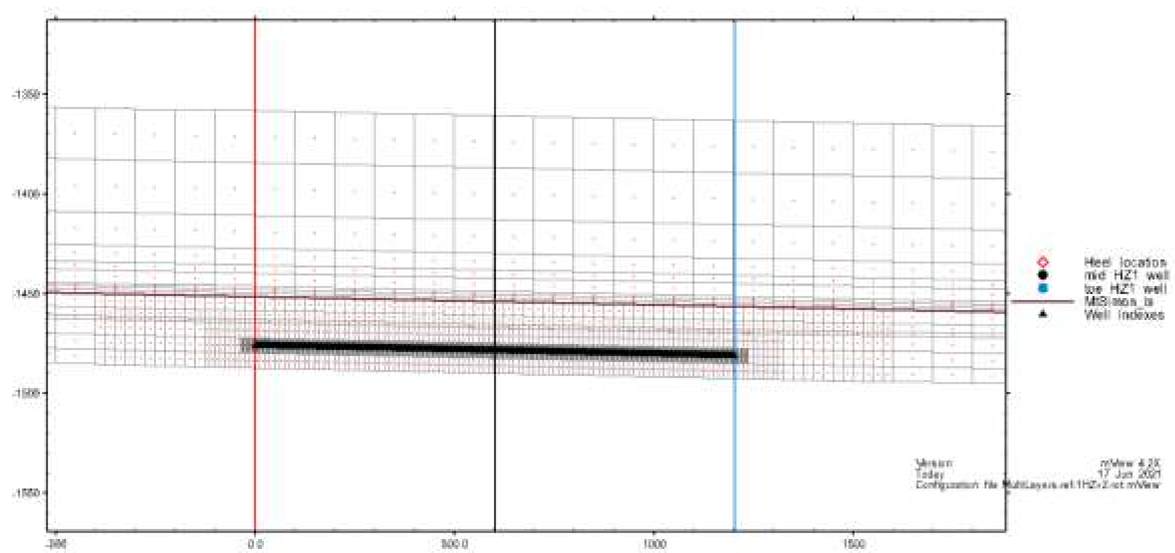

Figure 3-9 Model discretization SW-NE cross-section along the well – local datum

Table 3-2 3D Model Grid coordinates

Grid Center	636,446.5	181,608.8	
Grid Size	70,000	70,000	Cells
Grid Corners	587,700.9	173,013.6	SW
	627,851.3	230,354.3	NW
	685,191.9	190,203.9	NE
	645,041.6	132,863.3	SE

Table 3-3 3D Model Number of Nodes

Layer IDs	# layers	nodes/layer	# nodes
layers 6-9, A to E	9	2,560	23,040
layers 3-5	3	4,960	14,880
layer 2	1	6,700	6,700
layer 1	1	21,388	21,388
layer 0	1	6,700	6,700
Total	15		72,708

Table 3-4 3D Model Geologic Subunits

Model Layer	# of sub-layers	Formation	Formation thickness (m)	Geologic Sub-unit	Well 21819 Layer	Layer top (ft)	Layer bottom (ft)	thickness (m)	% of unit
A-E	5	Rome (caprock)	107.9	Rom_A	7-9	5,172	5,483	94.8	87.9%
9	1			Rom_B	10-11	5,483	5,508	7.6	7.1%
6-8	3			Rom_C	12	5,508	5,526	5.5	5.1%
5	1	MtSimon (reservoir)	28.1	Sim_A	13-14	5,526	5,544	5.5	19.5%
4	1			Sim_B	15	5,544	5,555	3.4	12.1%
3	1			Sim_C	16	5,555	5,560	1.5	5.3%
0-2	3			Sim_D	17-22	5,560	5,618	17.7	63.0%

3.3.2 INPUTS

The following is a summary of the various model inputs used for the 3D model.

- Fluid properties are constant throughout the model:
  - Brine properties (corresponding to 50,000 mg/L TDS): initial salt mass fraction of 0.049% by weight corresponding to a brine density of 1,025 kg/m^3.
  - Initial CO2 gas fraction of 0.0
- Rock properties are constant within each model layer as per Table 3-5 (overall reservoir perm.thickness is ~277 mD.m) and shown on Figures 3-10 to 3-12.
- Relative permeability and capillary functions for the Mt Simon and the Rome formations are described in Sections 2.4 and 2.5.

- Initial conditions:
  - Reservoir pressure gradient of 10.13 kPa/m and 75 mASL hydraulic head.
  - Thermal gradient of 25 C/km
- Total mass injection rate of 3.8 kg/s (120,000 t/year) equally split between wells.

Table 3-5 3D Model Rock Properties

Sensitive, Confidential, or Privileged Information

[redacted]

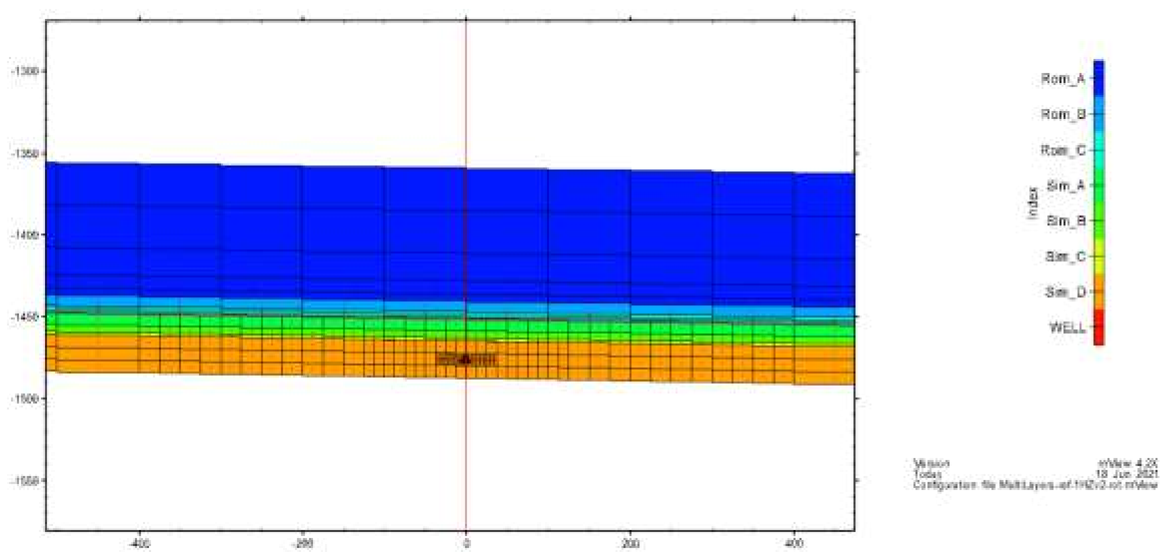

Figure 3-10 NW-SE cross-section perpendicular to well showing rock properties – local datum

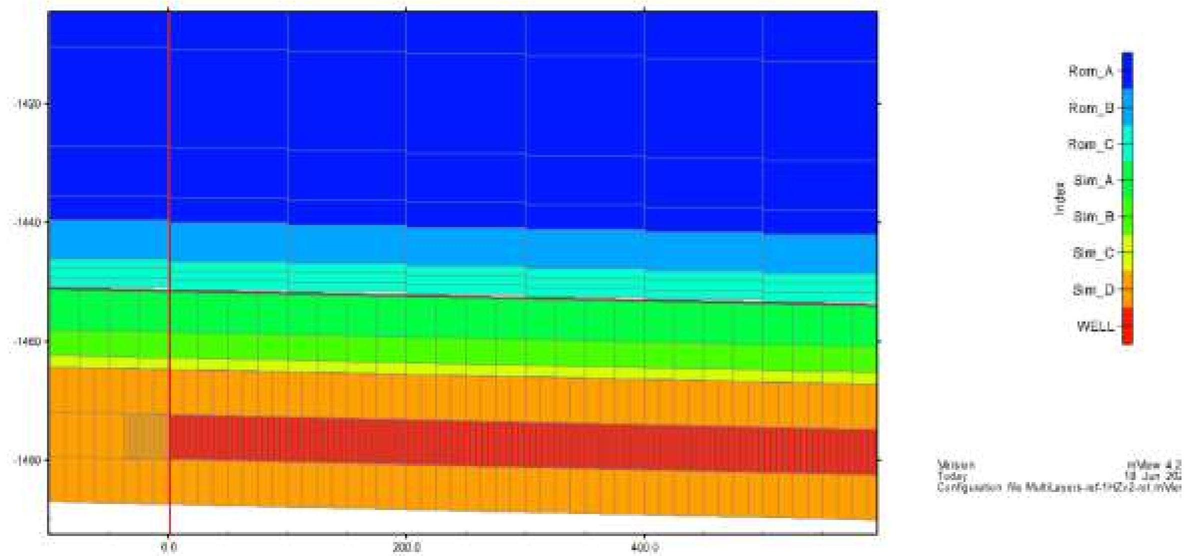

Figure 3-11 SW-NE cross-section along the well showing rock properties – local datum

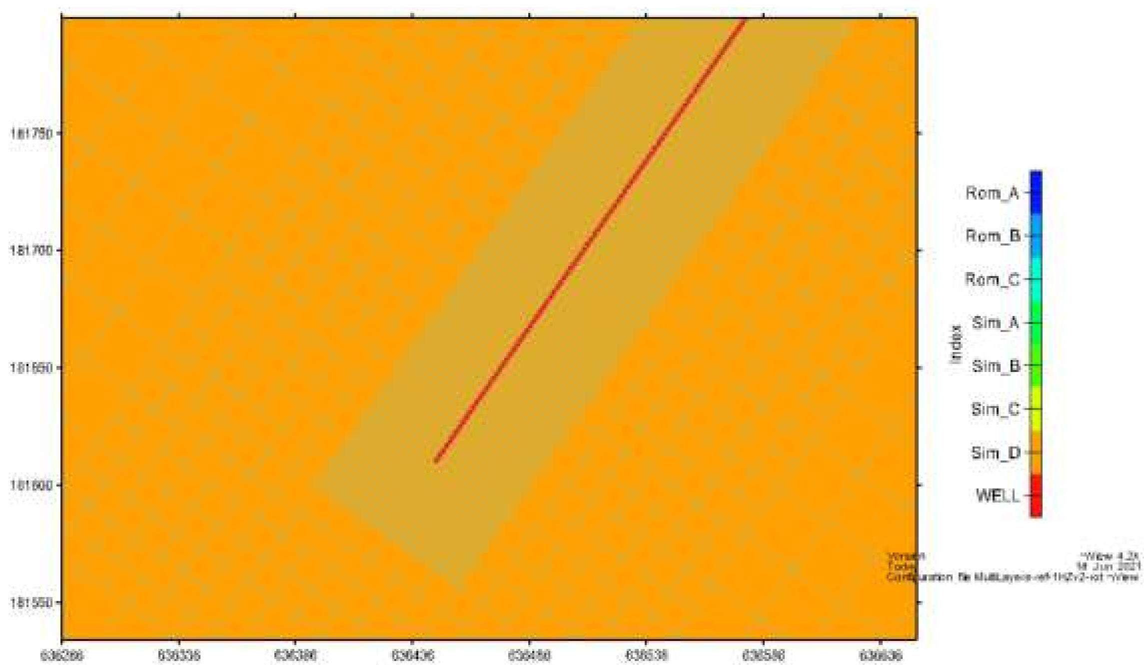

Figure 3-12 Plan View (Layer 1) showing rock properties – – UTM 1927 State Plane of Ohio North

3.3.3 RESULTS

3.3.3.1 TWO VERTICAL/DEVIATED WELLS

Two deviated wells with 800m separation downhole (this could also represent two vertical wells located 800m from each other), each injecting 60,000 tCO2/year, were evaluated. While the pressure build-up (6.5-7.0 MPa) was significantly less than with a single vertical well (Figure 3-13), it still exceeded the maximum allowable pressure buildup relative to the MOP (6MPa) such that the frac pressure is not exceeded. This means that two injection wells (either deviated or vertical) could not be comfortably drilled from a single well pad: either more downhole separation or a third well is necessary.

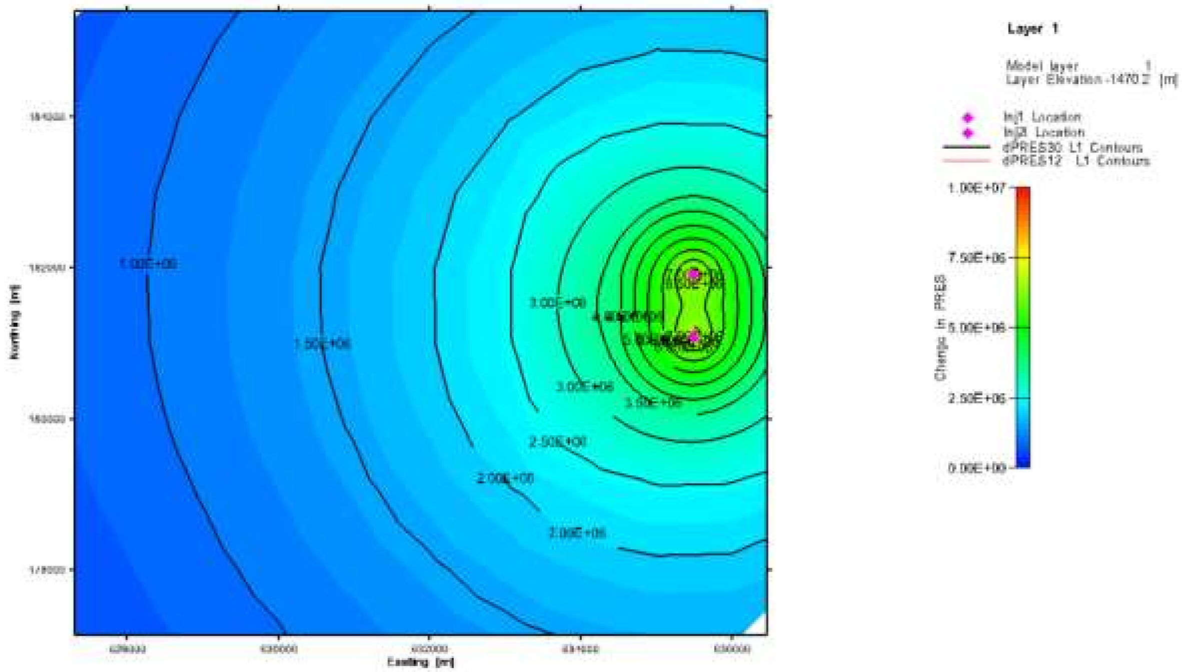

Figure 3-13 Plan View (Layer 1) showing the pressure build up after 30 years of injection – Two deviated wells

3.3.3.2 TWO SHORT HORIZONTAL WELLS

Two horizontal wells with a 400m horizontal leg and drilled from a single pad, with 800m separation heel to heel, were evaluated next. Figures 3-14 and 3-15 show that the pressure buildup after 30 years of operations remains below the maximum allowable pressure increase relative to the MOP.

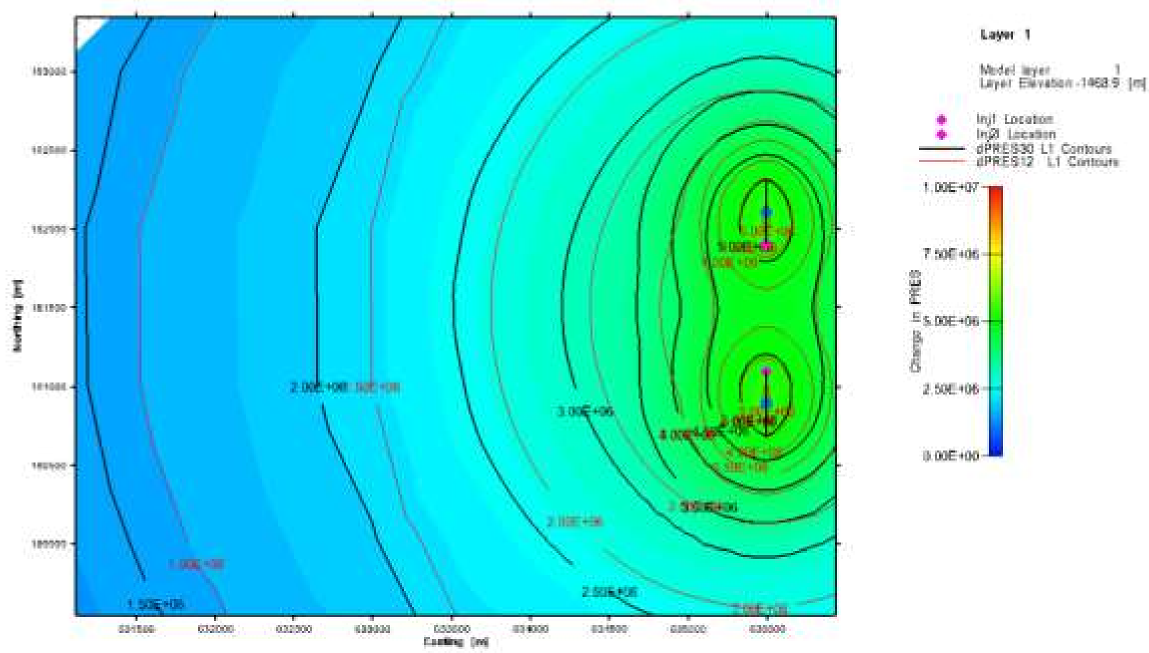

Figure 3-14 Plan View (Layer 1) showing the pressure build up after 30 years of injection – two 400m horizontal wells

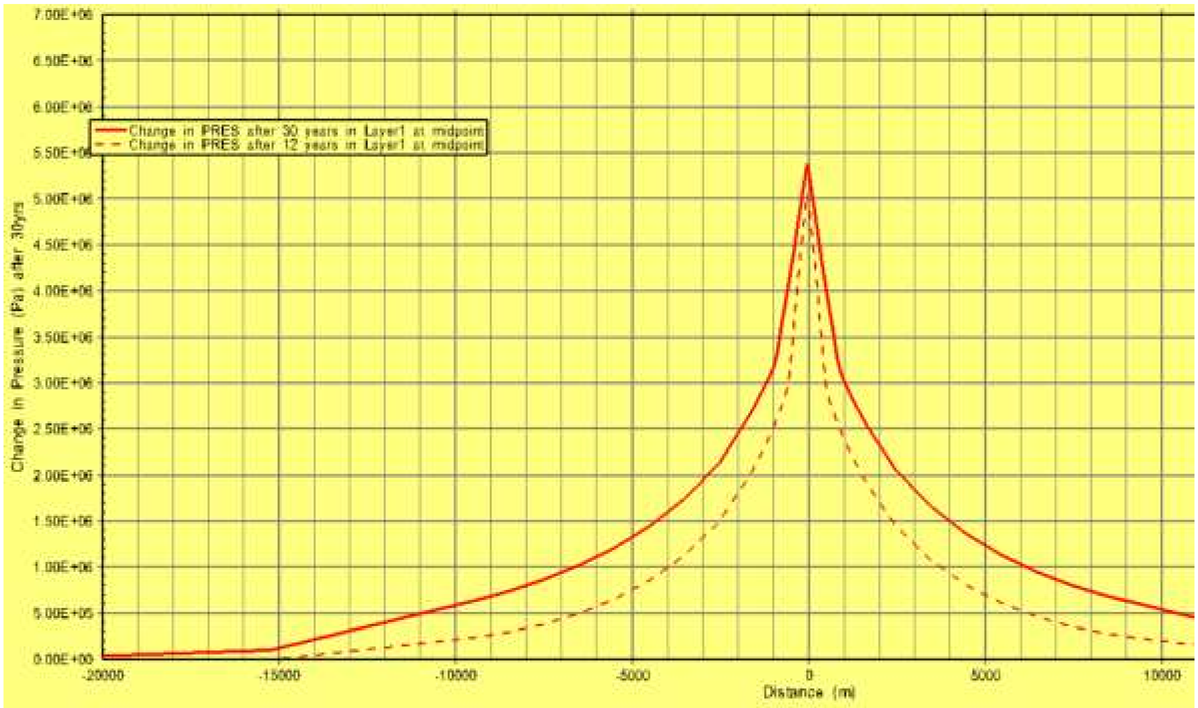

Figure 3-15 pressure build up after 30 years of injection vs. radial distance – two 400m horizontal wells

3.3.3.3 ONE LONG HORIZONTAL WELL

Although two 400m horizontal wells met the feasibility criteria from a reservoir perspective, it was deemed beneficial to have a single longer horizontal well from a project perspective. A single horizontal well with a 1200m long horizontal leg, entirely located underneath the landfill footprint and rotated clockwise 35 degrees from North, was evaluated in the final simulation.

Simulated Pressures and CO2 Saturations

Figures 3-16 and 3-17 show some time series of simulated reservoir pressures at selected nodes described below:

- Toe (node 11g08), mid-well (node 11089) and heel (node 10O49) of HZ well within the injection layer
- Just above the HZ well heel at the top of the reservoir (node 51740), at the base of the Rome confining unit (node 61038), in the lower third of the Rome confining unit (node A1038) and in the middle of the Rome (node C1038).

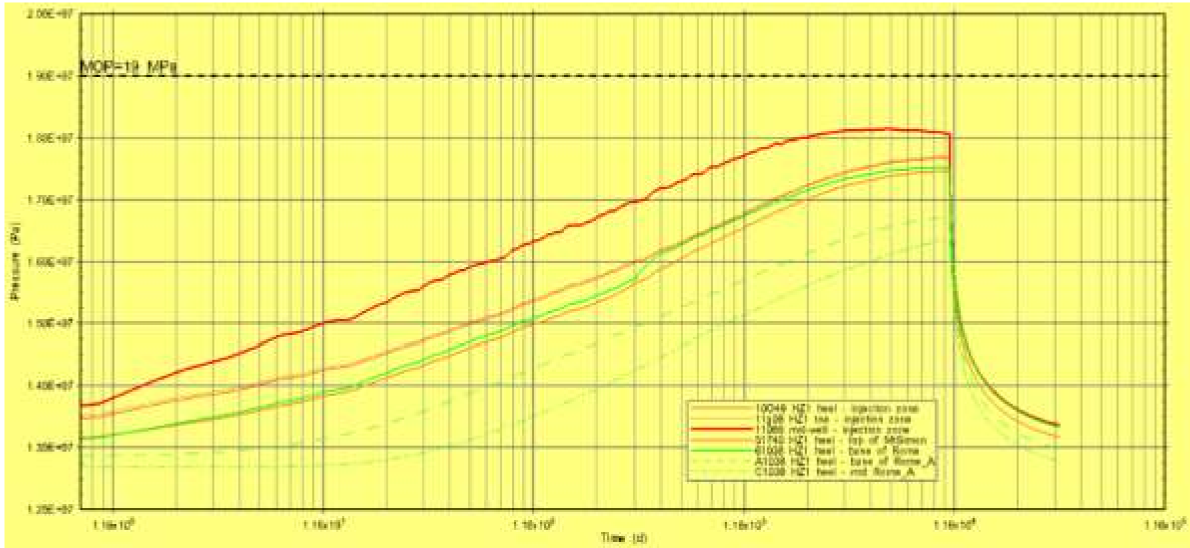

Figure 3-16 Pressure time series for 100 years at selected nodes

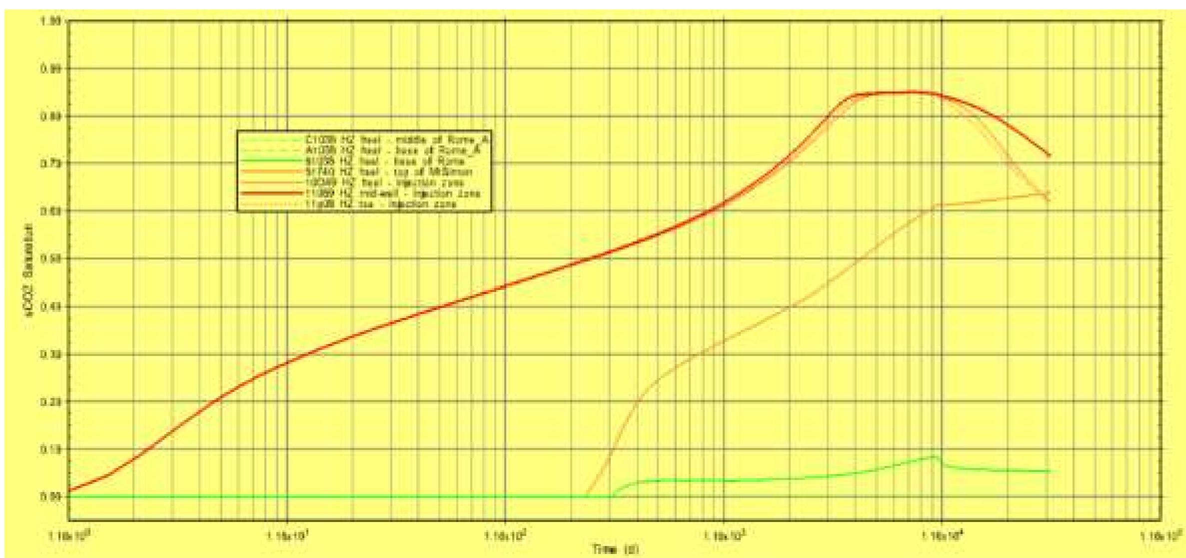

Figure 3-17 CO2 saturation (liquid) time series for 100 years at selected

Maximum Operating Pressure

Figures 3-18 to 3-20 show that the maximum reservoir pressure after 30 years of injection remains under the MOP of 19.1 MPa and that the corresponding pressure buildup remains well below the maximum allowable pressure increase relative to MOP (6.0 MPa).

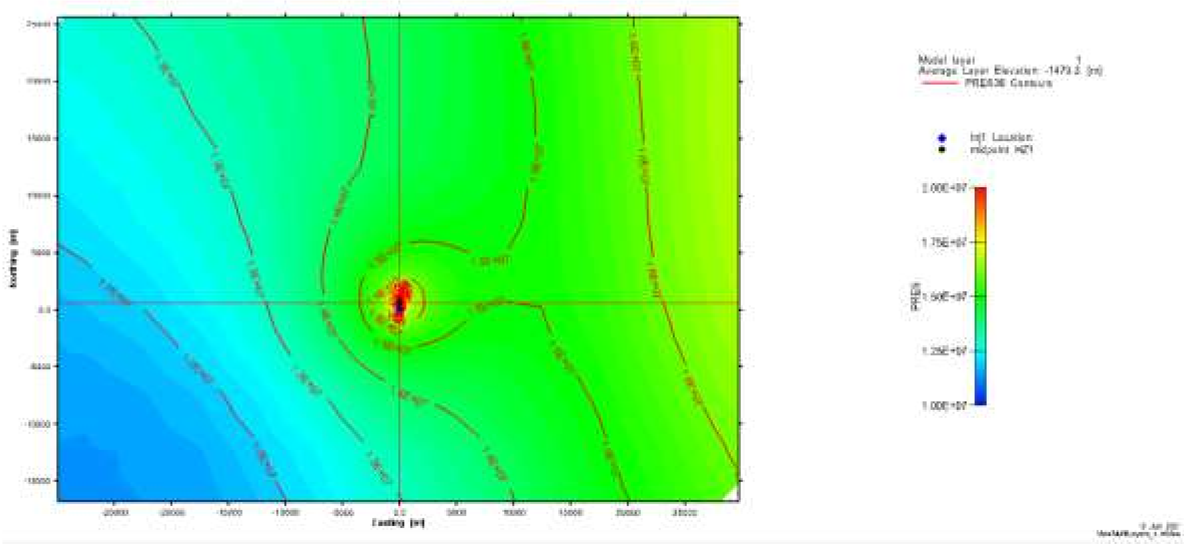

Figure 3-18 Plan view of pressure at the end of the injection period (30yrs) in injection layer (layer1) – local datum

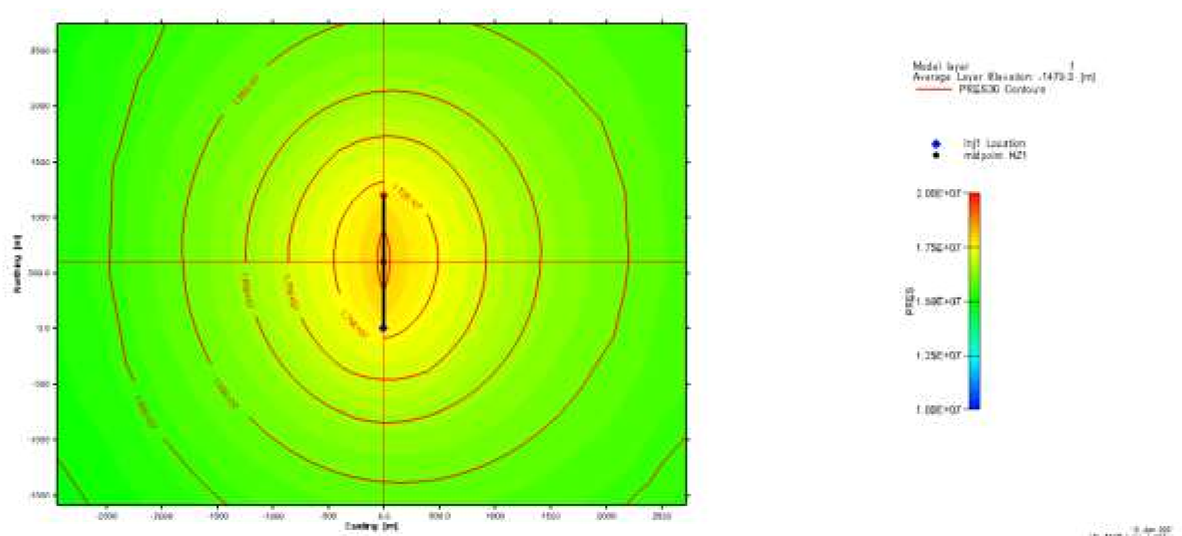

Figure 3-19 Plan view of pressure (zoomed in) at the end of the injection period (30yrs) in injection layer (layer1) – local datum

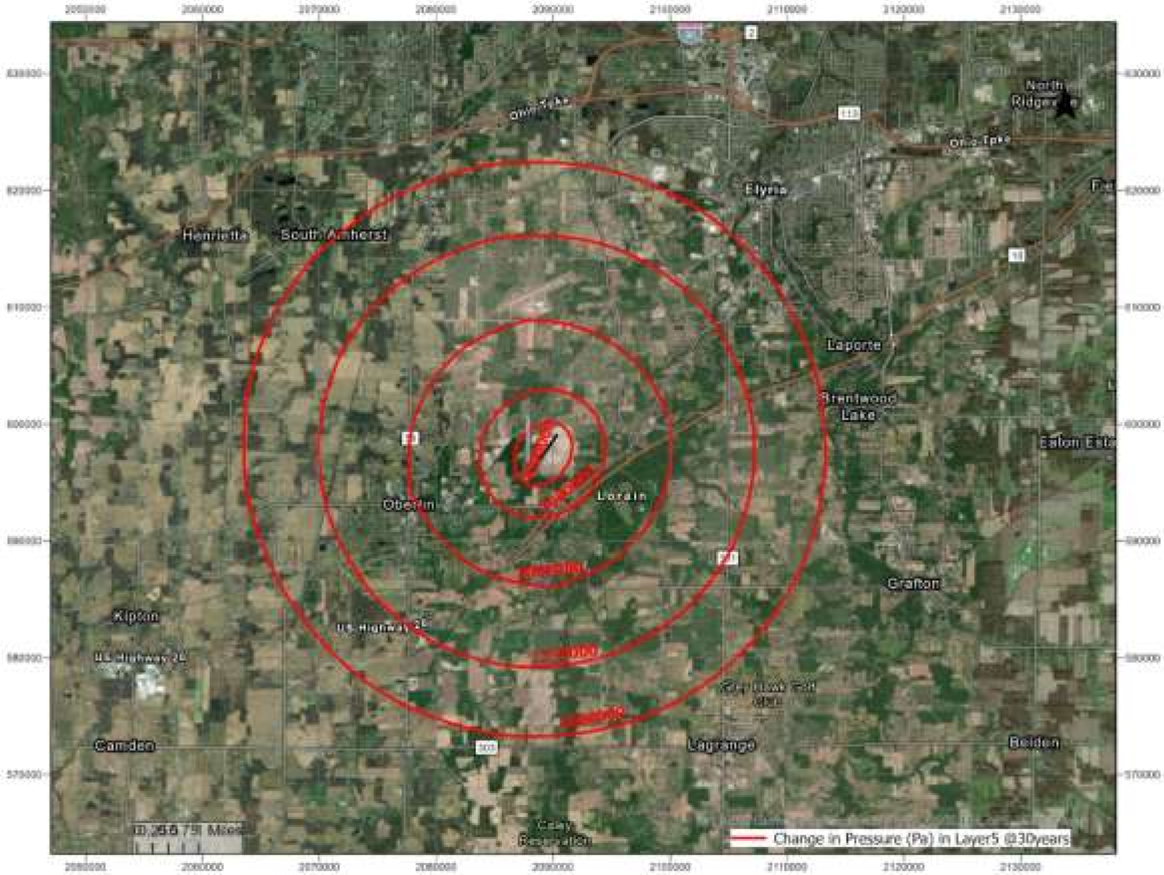

Figure 3-20 Plan view of change in pressure (Pa) at the end of the injection period (30yrs) at the top of the reservoir (layer5)

Area of Review

The area of review (AoR) is based on the Pressure Front contour (iso contour equal to 1.54 MPa; see Section 2.6.3) because the CO2 plume extent (1020m radius as shown by the liquid CO2 saturation after 30 years on Figure 3-22) is much smaller and is contained with the pressure front contour (5000m radius as shown by the pressure increase after 30 years on Figures 3-20 and 3-21). Therefore, the area of review for the single 1200m horizontal well is represented by the 0.10 liquid saturation contour shown on Figure 3-23.

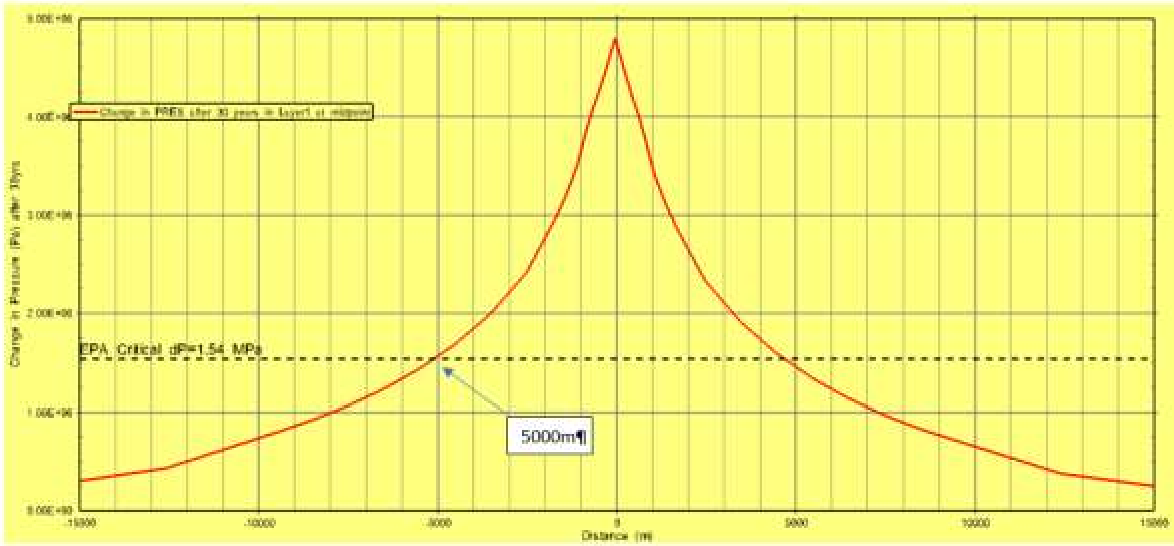

Figure 3-21 Change in pressure at the end of the injection period (30yrs) at the top of the reservoir (layer5) vs distance from HZ well

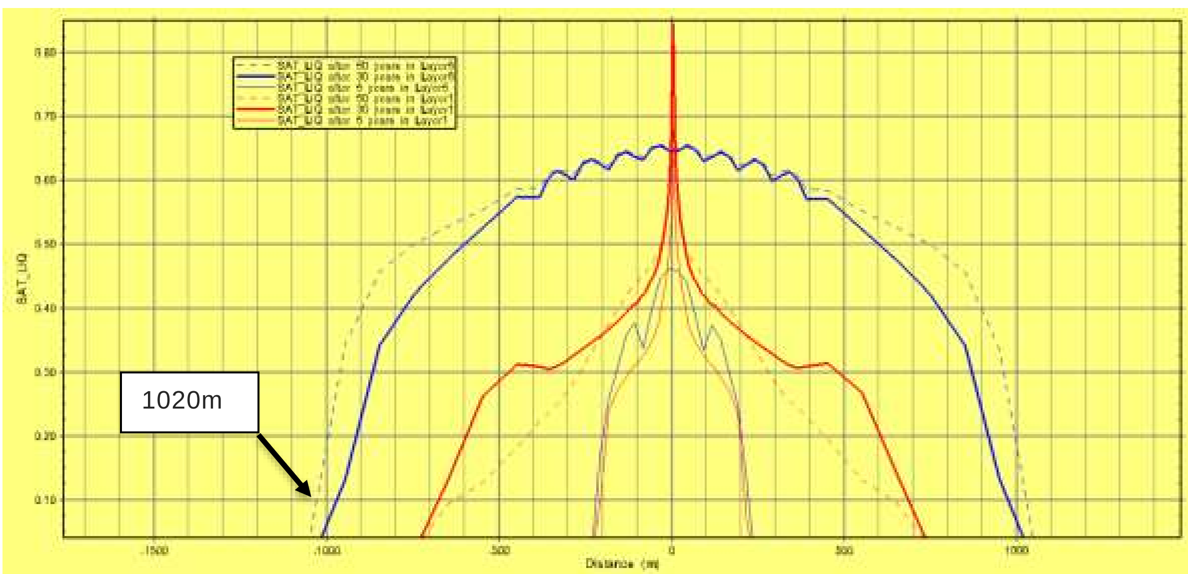

Figure 3-22 CO_2 saturation (liquid) vs radial distance at different time intervals in Layers 1 and 5

Figure 3-23 Plan view of CO_2 saturation (liquid) at the end of the injection period (30yrs) at the top of the reservoir (layer5) with 0.1 contour

CO_2 Containment

Figure 3-22 shows that the CO_2 plume areal extent is essentially stable once the injection well is shut in after 30 years of operations, although some vertical migration of the CO_2 is noted within the Mt Simon reservoir. Figure 3-24 shows that the sCO_2 is contained within the Mt Simon reservoir after 30 years.

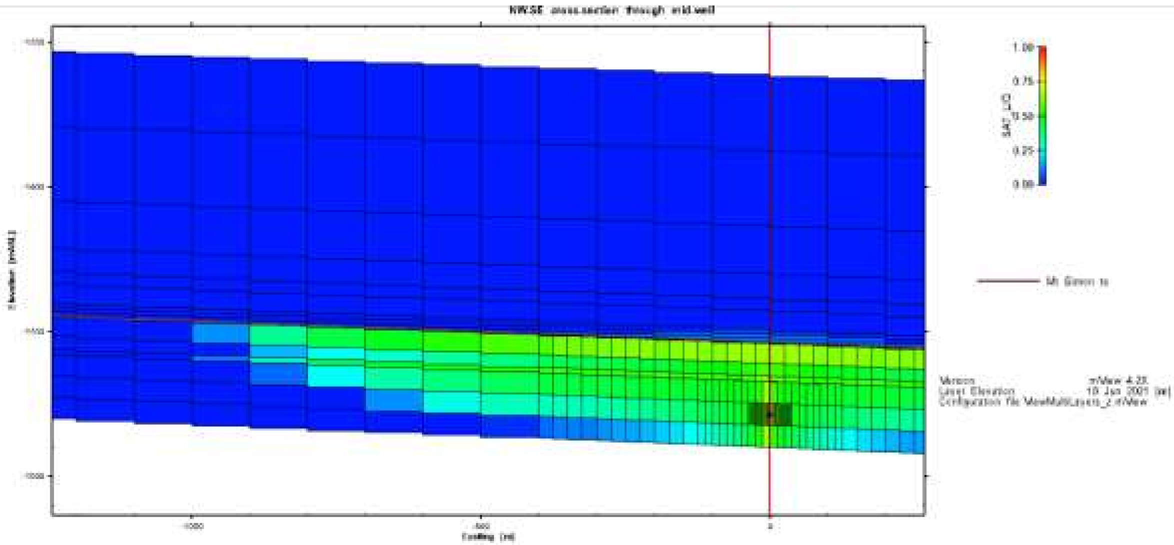

Figure 3-24 NW-SE cross-section perpendicular to the HZ well (mid-well) showing CO2 saturation (liquid) at the end of the injection period (30 years)

3.4 SENSITIVITY STUDY

A sensitivity study using the 3D model was conducted to better understand the impact of a number of reservoir and operational parameters on the project performance. The parameters that were varied from the base case values are listed below and shown on Table 3-6:

- Mt Simon reservoir porosity, horizontal permeability, compressibility, salinity, relative permeability and capillary pressure functions.
- Rome Formation vertical permeability.

Project performance was assessed using the following four metrics:

1) The difference between maximum simulated reservoir pressure and MOP after 30 years of injection
2) The pressure front distance in the injection layer after 30 years of injection
3) The CO_2 plume areal extent at the top of the reservoir after 30 years of injection
4) The CO_2 vertical migration into the Rome Fm after 30 years of injection as measured in the lower third of the Rome Fm (Layer A) at node A1120 (the element center is located 50m west of horizontal well).

The results of the sensitivity study are shown on Table 3-7. The most sensitive parameter is the horizontal permeability of the reservoir. Higher reservoir permeability causes a reduced pressure buildup in the reservoir which in turn reduces the distance to the pressure front, the areal extent of the CO_2 plume and the drive to push CO_2 vertically into the Rome Fm. A greater thickness also increases the perm.thickness of the reservoir with the same reservoir impacts described just above. However, the range of possible reservoir thicknesses is more constrained than the range of possible permeability values and, thus, the model results are less sensitive to probable reservoir thickness. Lower compressibility values have the opposite effect in that pressure buildups are increased with the corresponding increase in distance to pressure front, CO_2 plume extent and more CO_2 vertical migration.

A greater porosity is also found to decrease the areal extent of the CO_2 due to an increased pore volume in the reservoir and thus a greater CO_2 storage capacity. Finally, a lower capillary pressure results in increased CO_2 vertical migration as it makes it easier for the CO_2 to replace the brine in the pore space.

Table 3-6 Sensitivity Study Parameters

Sensitive, Confidential, or Privileged Information

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Table 3-7 Sensitivity Study Results

Sensitive, Confidential, or Privileged Information

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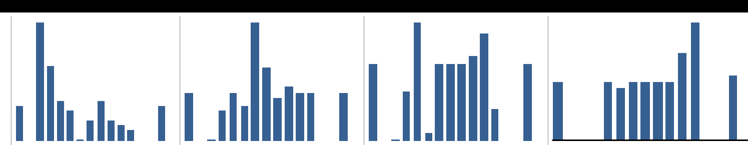

3.5 MODEL LIMITATIONS

- There are few Mt Simon reservoir penetrations in the study area; reservoir data uncertainty varies accordingly.
- The reservoir character/vertical discretization is constant throughout the model and based on the petrophysical log analysis of Well 21819.
- No regional or local faults have been identified therefore reservoir faulting is not represented in the 3D model.
- The reservoir properties (permeability, compressibility) are constant throughout the model based on the petrophysical analysis of a wells; there are no core nor well test data available for the study area.
- The predicted changes in pressure and sCO_2 saturation only pertain to the reservoir. The model does not account for wellbore dynamics or well skin.

- Hysteresis is not considered in the relative permeability curves. Modeled reservoir dip and regional pressure gradient indicates minimal to no regional brine flow therefore impact to plume extent and CO_2 imbibition was considered insignificant.

4.0 CONCLUSIONS

Simulation results indicate that a single vertical well would not provide the required 120,000 t/year sCO2 injection capacity into the Mt Simon Formation at the Lorain County landfill given the current understanding of reservoir properties. A single 1200m long horizontal well was found to be sufficient. Alternatively, two deviated or shorter horizontal wells could be considered provided that their design include sufficient downhole separation.

The Area of Review distance calculated from the 3D model for the single 1200m horizontal well is 5000m around the horizontal well based on the pressure front calculation. However, the sCO2 plume areal extent is only 1000m after 30 years of operations. Finally, the Rome Formation acts as a suitable confining unit and contains the injected sCO2 within the Mt Simon reservoir.

The simulation results and conclusions presented in this report are based on the limited amount of data available for the area, including few well penetrations in the Mt Simon reservoir and none at the Lorain landfill site.

5.0 REFERENCES

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Janseens, A., (1973) *Stratigraphy of the Cambrian and Lower Ordovician Rocks in Ohio,* Ohio Geological Survey, Bulletin 64

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US EPA (2013). *EPA 816-R-13-005. Geologic Sequestration of Carbon Dioxide. Underground Injection Control (UIC) Program Class VI Well Area of Review Evaluation and Corrective Action Guidance. May 2013.*

APPENDIX

5-1 DRILLING PROGRAM

Operator Name: Lorain Carbon Zero Solutions, LLC
Well: CCS #1
Permit Number: TBD
API No.: TBD
State: Ohio
County: Lorain

Survey: TBD
Abstract: TBD
Field: TBD
Lease: TBD
EPA Region: 5
TRRC Phone: TBD

LORAIN COUNTY LANDFILL LOCATION:

43502 Oberlin Elyria Rd
Oberlin, OH 44074

WELL LOCATION:

Surface location (estimate):
Latitude: 41.30072004268709, Longitude: -82.18020889479159

Ground Elevation: 785 ft MSL
KB Elevation: TBD (~25 ft above GL)

WELLBORE CONFIGURATION AND CASING PROGRAM

Proposed wellbore configuration:

24”, 246 lb/ft, J-55, New, Conductor Pipe: 0 - Approx. 200 feet BGL. (Augured)
16”, 84 lb/ft, New, J-55, BTC, Surface Casing: 0 - Approx. 1000 ft. KB (18 1/8” Hole)
10 3/4”, 45.5 lb/ft, New, HCN-80, STC, Intermediate Casing: 0 – Approx. 4,445 ft. MD KB (14 3/4” Hole)
7”, 26 lb/ft, New, N-80, STC, Carbon Steel Longstring Casing: 0 – Approx. 4400 ft. MD KB (9 ½” Hole) w/ 10’ stage tool
7”, 26 lb/ft, New, VM-80, VAM TOP, 13 Chrome Longstring Casing: 4410 ft. MD KB – Approx. 5000 ft. MD KB (4845’ TVD) (9 ½” Hole)
Open Hole Section: 6 ¼ inch lateral completion from 5000 ft. MD KB – 8937 ft. MD KB

3 ½", 9.3 lb/ft, J-55, VAM FJ, STC tubing from the packer (approximately 4,430 MD KB) to the surface
Total Depth: Approx. 8,937 ft MD KB (4,845 ft TVD)

Note: ALL depths are approximate. The actual depths will vary by rig.

OBJECTIVE

Drill a ~8,937 ft KB MD CO_2 injection well into the Mount Simon target zone at 4845 ft KB TVD (8,937 ft KB MD). The well is designed to safely inject CO_2 into the reservoir at an injection rate needed by the client.

WORK SEQUENCING PLAN

Location Preparation

Move in equipment for preparing the location by constructing an 8-foot diameter, 6-foot-deep cellar utilizing corrugated steel lining. Augured, 24", 246 lb/ft, J-55 Conductor to 200 ft GL. Grout the annulus to the surface and the bottom of the cellar, with ready mix concrete. Augur in a 40 ft mouse hole and install 14" mousehole casing.

Drilling

Installing 16" Surface Casing

1. Move in and rig up drilling rig and all associated drilling equipment provided by the drilling contractor. Nipple up using the excess 24" Conductor. Install (2) 2" outlets with ball valves just below ground level on the conductor casing to drain excess cement after the surface casing has been cemented. Rig up a closed loop solids control system to separate drill cuttings and drilling fluids, with the dry cuttings land farmed at the request of the landowner (if possible). Function test all rig equipment for proper operation and perform a rig safety inspection prior to spudding the well. All cuttings will be collected in steel boxes during drilling operations and all excess drilling fluid will be stored in frac tanks. Fluids will be disposed off-site at a licensed disposal well.

2. Build a freshwater spud mud according to proper mud specifications as directed by the mud engineer.

3. Rig up the mud loggers. Plan on catching 20-ft samples to 1000± ft KB and then 10-ft samples from 1000 ft to total depth.

4. Make up the 18 1/8" drilling bit and bottomhole assembly (BHA).

5. Clean out the 24" Conductor.

6. Drill the surface hole to ~1000 ft± KB (Surface Casing Point). The actual depth will be determined by the USDW. Drill the hole to fit the casing as closely as possible. Run surveys every 30 ft below the Conductor, and at total depth. Pump Hi-Vis sweeps as necessary to clean the hole.

7. Pump a ~60 bbl 80+ Hi-Vis sweep. Make a wiper trip to the Conductor. Pump a ~60 bbl, 80+ Hi-Vis sweep. Circulate the hole clean.

8. Trip out of the hole. Lay down the stabilizers and bit.

9. Rig up wireline logging company and run a triple combo log and a 4-arm caliper to obtain the wellbore volumes for cementing. The caliper tool will need arms to go to 24" minimum. All logs (all logs run in this project) should be zero'd at KB and have a 5" = 100' presentation.

10. An additional wiper run may be necessary, depending on the caliper log results.

11. Move in and rig up the casing crew and all the necessary equipment to run the 16" casing.

12. Make up (and Baker-LOC) a cement guide shoe and float collar on opposite ends of the first joint. Run ±1000 ft of 16", 84 lb/ft, J-55, BTC, Surface Casing. Attach two centralizers on the shoe joint and one centralizer every joint to surface. Tag the bottom of the 18 1/8" hole with the casing, then pull the shoe less than one (1) foot off bottom.

13. Circulate and condition the drilling fluid until hole is clean and at least 1.5 times the casing volume has been pumped. No "thick" mud should be in the returns.

14. Cement the casing in place with 530 sacks (25% excess in open hole) of Class A 15.8 ppg (Halcem or equivalent), 1.175 ft3/sk yield cement. Chain the casing down to the substructure prior to cementing. It will attempt to float.

15. Collect three wet samples of lead and tail mixes and one dry sample.

16. Cement returns should be seen at surface. Center the casing best as possible. If no cement returns are observed at the surface, run a Temperature Log to determine the top of the cement after 8 hours. Use 1" tremie pipe to top out cement to ensure cement in the annulus is at the surface, if necessary. Drain the excess cement through the 2" outlet in the conductor casing. Center the casing inside the Conductor as best as possible.

17. Wait on the cement at least 24 hours before touching the casing. The cement should have a minimum compressive strength of 500 psi prior to continuing.

18. Run cement bond log from the float collar to the surface.

19. Cut down the 24" Conductor and 16" Surface Casing as necessary. Weld on the specified 16-3/4", 3M casinghead. Test the void on the casinghead to the manufacturer's recommendation.

20. Nipple up a swage adaptor from 16-3/4" to 21-1/4", one/two drilling/spacer spools, as necessary, a 21-1/4", 3M drilling spool, and a 21-1/4" annular. Pressure test the annular BOPE by closing it and chart the pressure tests.

21. Pressure test the Surface Casing to 1000 psig WHP. Record the test on a chart.

22. Install a wear bushing.

<u>Installing 10 3/4" Intermediate Casing</u>

23. Trip in hole with the 14 3/4" bit assembly.

24. Drill out the float collar, casing shoe and 5 ft of new formation.

25. Circulate the hole clean.

26. Run a Formation Integrity Test to 10.0 ppg equivalent.

27. Continue drilling the 14 ¾" hole to casing point at 4445 feet. Drill the hole to fit the casing as closely as possible. Run surveys every 30 ft below the surface casing and at total depth. Pump hi-vis sweeps as necessary to clean the hole.
28. Pump a ~60 bbl 80+ hi-vis sweep. Make a wiper trip to the surface casing. Pump a ~60 bbl, 80+ hi-vis sweep. Circulate the hole clean.

29. Trip out of the hole. Lay down the stabilizers and bit.

30. Rig up wireline logging company and run a triple combo log and a 4-arm caliper to obtain the wellbore volumes for cementing.

31. An additional wiper run may be necessary, depending on the caliper log results.

32. Move in and rig up the casing crew and all the necessary equipment to run the 10 3/4" casing.

33. Make up (and Baker-LOC) a cement guide shoe and float collar on opposite ends of the first joint. Run ±4445 ft of 10 3/4", 45.5 lb/ft, HCN-80,STC, Intermediate Casing. Attach two centralizers on the shoe joint and one centralizer every joint to surface. Tag the bottom of the 14 3/4" hole with the casing, then pull the shoe less than one (1) foot off bottom.

34. Circulate and condition the drilling fluid until hole is clean and at least 1.5 times the casing volume has been pumped. No "thick" mud should be in the returns.

35. Cement the casing in place with 2245 sacks of 15 ppg, 1.345 ft3/sk yield, Class H cement (NeoCem or equivalent). Chain the casing down to the substructure prior to cementing. It will attempt to float.

36. Collect three wet samples of lead and tail mixes and one dry sample.

37. Cement returns should be seen at surface. Center the casing best as possible. If no cement returns are observed at the surface, run a Temperature Log to determine the top of the cement after 8 hours. Use 1" tremie pipe to top out cement to ensure cement in the annulus is at the surface, if necessary. Drain the excess cement through the 2” outlet in the conductor casing. Center the casing inside the Conductor as best as possible.

38. Wait on the cement at least 24 hours before touching the casing. The cement should have a minimum compressive strength of 500 psi prior to continuing.

39. Run cement bond log from the float collar to the surface.

40. Cut down the 16” Surface Casing and 10 3/4” Intermediate Casing as necessary. Weld on the specified SOW 11”, 5M casinghead. Test the void on the casinghead to the manufacturer’s recommendation.

41. Nipple up one/two drilling/spacer spools, as necessary, a 11”, 5M drilling spool, blind rams, pipe rams, annular, bell nipple, choke manifold, and flow line. Pressure test the BOPE and chart the pressure tests.

42. Pressure test the Intermediate Casing to 1000 psig WHP. Record the test on a chart.

43. Install a wear bushing.

<u>Installing 7” Production Casing</u>

44. Trip in hole with the 9 1/2” bit assembly.

45. Drill out the float collar, casing shoe and 5 ft of new formation.

46. Circulate the hole clean.

47. Run a Formation Integrity Test to 10.0 ppg equivalent.

48. Continue drilling the 9 1/2” hole to the first core point in the Confining Zone at ~4620 ft KB.

49. Trip out of the hole with drilling BHA and install coring BHA assembly and trip to 4620 ft KB.

50. Obtain a 30-ft core from 4620 to 4650 ft. Trip out of the hole with the coring BHA assembly.
51. Trip in the hole with 9 ½" bit assembly and continue drilling 9 1/2" hole to second core point at ~4860 ft KB (Mount Simon Injection Zone).
52. Trip out of the hole with drilling BHA and install coring BHA assembly and trip to 4860 ft KB.
53. Obtain a 30-ft core from 4860 to 4890 ft. Trip out of the hole with the coring BHA assembly.
54. Trip in the hole with 9 ½" bit assembly and continue drilling 9 1/2" hole to third core point at ~4950 ft KB (Mount Simon Injection Zone)
55. Trip out of the hole with drilling BHA and install coring BHA assembly and trip to 4950 ft KB.
56. Obtain a 30-ft core from 4950 to 4980 ft. Trip out of the hole with the coring BHA assembly.
57. Trip in the hole with 9 ½" bit assembly and continue drilling 9 1/2" hole to 5000 ft KB.
58. Pump a ~60 bbl 80+ hi-vis sweep. Make a wiper trip to the intermediate casing. Pump a ~60 bbl, 80+ hi-vis sweep. Circulate the hole clean.
59. Rig up wireline logging company and run a triple combo log, resistivity, porosity, micro-imaging and fracture finder logs. Run a 4-arm caliper log to determine cement volume for cement plug. Analyze logs to determine best location to drill the lateral in the Mount Simon lateral.
60. Trip in the hole with drill pipe open-ended at 5000 ft. Rig up cement truck and pump ~100 bbls (will change based on calipered volume) of Class H cement to have plug top at 4150 ft.
61. Wait on cement for 12 hours. Run in with drill pipe and tag cement to see if hard.
62. If cement is tagged, trip out of the hole with drill pipe and install 9 ½" bit assembly with MWD tool (with gamma ray) and drilling motor.
63. Start drilling the curve from 4150 ft to the entrance of the lateral (90 deg inclination) at 4845 ft TVD (5000 MD). Run surveys every 30 ft below the intermediate casing and at total depth. Pump hi-vis sweeps as necessary to clean the hole.
64. Pump a ~60 bbl 80+ hi-vis sweep. Make a wiper trip to the intermediate casing. Pump a ~60 bbl, 80+ hi-vis sweep. Circulate the hole clean.
65. Trip out of the hole. Lay down the stabilizers and bit.

66. Rig up wireline logging company and run a 4-arm caliper to obtain the wellbore volumes for cementing.

67. An additional wiper run may be necessary, depending on the caliper log results.

68. Move in and rig up the casing crew and all the necessary equipment to run the 7” casing.

69. Make up (and Baker-LOC) a cement guide shoe and float collar on opposite ends of the first joint. Run ±5000 ft of 7”, 26 lb/ft, VM-80, STC, Longstring Casing. Attach two centralizers on the shoe joint and one centralizer every joint to surface. Tag the bottom of the 9 1/2” hole with the casing, then pull the shoe less than one (1) foot off bottom.

70. Circulate and condition the drilling fluid until hole is clean and at least 1.5 times the casing volume has been pumped. No “thick” mud should be in the returns.
71. Cement the 7” casing in place in two stages using the DV tool. The first stage is comprised of 32 bbls of CO_2-resistant cement material (9.2 ppg WellLock or equivalent). The second stage is 895 sacks of 15 ppg, 1.345 ft3/sk yield, Class H (NeoCem or equivalent) Portland cement. **Displace with the first stage with fresh water on the bottom and mud on the top. Displace the second stage with only fresh water.**

    - Wait 12 hours before pumping the second stage. Circulate mud slowly thru the DV tool while waiting.

    - Collect three wet samples of lead and tail mixes and one dry sample each, from both stages. The goal is to bring cement to surface.

72. Flush the BOPE stack out after both stages.

73. If cement circulates to surface with second stage, raise the stack, make a rough cut on the 7” and set the slips. Nipple up the BOPE and flow lines back up.
    - **If cement does not circulate to surface on the second stage. Run a Temperature Log (Baker Hughes Wireline) after 8 hours. If necessary, cement the annulus to surface with 1" tremie pipe. THEN raise the stack, cut and set the slips.**

74. Wait a minimum of 60 hours on cement, after the second stage. The cement should have a minimum compressive strength of 500 psi prior to continuing.

75. Run cement bond log from the float collar to the surface.

76. Cut down the 10 3/4” Intermediate Casing and 7” Production Casing as necessary. Weld on the specified SOW 7 1/16”, 5M tubinghead. Test the void on the tubinghead to the manufacturer’s recommendation.

77. Nipple up one/two drilling/spacer spools, as necessary, a 7 1/16”, 5M drilling spool, blind rams, pipe rams, annular, bell nipple, choke manifold, and flow line. Pressure test the BOPE and chart the pressure tests.

78. Pressure test the Production Casing to 1000 psig WHP. Record the test on a chart.

79. Install a wear bushing.

<u>Drilling 6 ¼" lateral</u>

80. Trip in hole with the 6 1/4" bit assembly including MWD, drilling motor, and micro-resistivity real-time tool.

81. Drill out the float collar, casing shoe and 5 ft of new formation.

82. Circulate the hole clean.

83. Run a Formation Integrity Test to 10.0 ppg equivalent.

84. Drill the 6-1/4" lateral hole to 8937 ft MD (4845 ft TVD). **Keep the hole full at all times. Closely monitor the required fill or displacement during trips.** Run surveys every 30 ft past the Production casing shoe, and at total depth. Pump Hi-Vis sweeps as necessary to clean the hole. Monitor real-time resistivity to confirm drilling lateral in the best layer of Mount Simon (as based on previous open hole resistivity logs).

85. Trip out of the hole and laydown the directional BHA.

86. Pick up the ThruBit BHA (logging tools).

87. Trip in the hole to total depth.

88. Circulate the hole clean.

89. Rig up Schlumberger ThruBit loggers and run QuadCombo w/ a FMI (imaging logs) logs as directed by the logging engineer. Log from the total depth to the longstring casing shoe as directed by the logging engineer. **Run the resistivity tools first. Any tools with a source will be run last, after determining the hole/fluid stability.**

    - **Running the ThruBit logs will depend upon how the hole is behaving.**
    - **Note: The logging tools will probably have to be broken down and two/three runs made to get as close to total depth as possible.**

90. Trip out of the hole, retrieving the ThruBit tools, standing back the drill string.

91. Trip in the well open-ended and fill the wellbore with fresh, clean water.

92. Observe the wellbore fluid level for one hour, to ensure that the well is stable

93. Nipple down the BOPE, bell nipple, flow line, etc.

94. Cut down and dress the Production Casing as necessary for a finish cut. Nipple up the next wellhead section including the 7 $^{1}/_{16}$” master valve. Test the P-Seals on the 7” bonnet to the manufacturer’s recommendation. Put a night cap on the wellhead.

95. Rig down and release the drilling rig and all associated drilling equipment and vendors. Dispose of all remaining cuttings as requested by the landowner. Solids control will send “dirty” water to the frac tanks as the pits are cleaned. Dispose of all remaining drilling fluids in an approved disposal well. Clean and spot the frac tanks off to the side, out of the way of the rig move.

96. Wait on completion.

Completion – Daylight Only

97. Move in a wireline unit and with 4 $^{5}/_{8}$” OD lubricator, with a 7 $^{1}/_{16}$” ,5M flange on the bottom.

98. Rig up Baker Wireline and run the HRVRT/Digital MicroVertilog on the ECoil from PBTD (5000± ft KB MD) to the surface to capture a baseline casing inspection log on the 7” casing. Lay down the VRT tool.

99. Rig up wireline with enough lubricator and a pump in sub (min 7 $^{1}/_{16}$” ID) to swallow a CCL, setting tools and the injection packer assembly on the 7 $^{1}/_{16}$” Master Valve.

100. Pick up the injection packer, dressed for 26 lb/ ft casing and run in the wellbore. Set the packer ~30 ft below the DV Tool, (4430± ft KB MD, approximate inclination 27 degrees), in the middle of a joint.

101. Rig down and release the loggers. Leave the hole full of fresh water. Shut the well in and secure it.

102. Move in a workover unit.

103. Nipple up the bonnet to hang the 3 ½” tubing under the 7 $^{1}/_{16}$” Master Valve.

104. Nipple up 7 $^{1}/_{16}$” x 5M BOPE.

105. Rig up the casing crew, torque turn, and internal pressure test crews and equipment.

106. Run approximately 4,430± of 3 ½”, 9.3 lb/ft, J-55, VAM FJ tubing.

107. Torque turn and test each connection internally to 4000 psi with helium.

108. Follow the packer tech's directions. Space out. Then displace corrosion inhibitor (approximately 2 bbls & fresh water) down the backside. *Note: that a set of 3 ½" pup joints will be available.*

109. Sting into the packer.

110. Do a quick pressure test on the casing/tubing annulus (backside) following the packer tech's recommendations.

111. After landing the mandrel, run in the six lock down pins. Test any P-Seals to the manufacture's recommendations.

112. Conduct a "practice" MIT type test on the annulus, 500 psi for 30 minutes.

113. Rig down and release the workover rig.

APPENDIX

5-2 DIRECTIONAL PLAN

Sensitive, Confidential, or Privileged Information

[redacted]

PHOENIX
TECHNOLOGY SERVICES

WSP

Lorain County, OH (ONZ - NAD83)
Lorain County Landfill
Class VI

OH

Plan: Plan 1 03-30-21

Standard Planning Report

30 March, 2021

Sensitive, Confidential, or Privileged Information

[redacted]

Sensitive, Confidential, or Privileged Information

[redacted]

Sensitive, Confidential, or Privileged Information

[redacted]

APPENDIX

5-3 HALLIBURTON CEMENTING VOLUMES

HALLIBURTON

WSP USA INC -EBUS
DONOTMAIL-16200 PARK ROW STE 200
HOUSTON, TX, 77084
US

LORAIN CARBON ZERO SOLUTIONS 1

Lorain County, OH, US

Cementing Cost Estimate

Proposal 399846 - Version 2.0
July 31, 2021

Submitted by:
Cole Pavlock
3000 N Sam Houston Pkwy E
Houston, TX - 770323219
USA

HALLIBURTON