PRELIMINARY REPORT
ON THE NORTHSTAR 1 CLASS II INJECTION WELL
AND THE SEISMIC EVENTS
IN THE YOUNGSTOWN, OHIO, AREA

Ohio Department of Natural Resources • March 2012

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EXECUTIVE SUMMARY

Youngstown Earthquakes

Since March 2011, the Youngstown area has experienced 12 low-magnitude seismic events along a previously unknown fault line. These events ranged from 2.1- to 4.0-magnitude and were recorded by the Ohio Department of Natural Resources' (ODNR) Ohio Seismic Network (OhioSeis). The network works closely with the U.S. Geological Survey to monitor and study all seismic activity within the state. (Ohio Seismic Network)

Prior to the network's establishment in 1999, monitoring earthquakes in Ohio was sporadic at best. In fact, before the network was operational, the Ohio Geological Survey was unable to accurately determine any seismic events below an approximate magnitude of 3.0. A station at Youngstown State University joined the network in 2003.

Before 2011, OhioSeis had not recorded earthquake activity with epicenters located in the Youngstown area. Also, no fault line had been previously mapped within the boundaries of Youngstown or Mahoning County. However, the broad geographical area does have a history of seismic activity, and Mahoning Valley residents have felt earthquakes from nearby faults. In fact, the area has experienced at least three prior earthquakes in the past 25 years. These events include: a 5.2-magnitude earthquake originating in Mercer County, Pa., in September 1998; a 5.0-magnitude earthquake in Lake County, Ohio, in January 1986; and a 3.0-magnitude earthquake in Portage County, Ohio, in August 2000. (Ohio Earthquakes)

Northstar 1 Class II Deep Injection Well

The 2011 earthquakes are distinct from previous seismic activity in the region because of their proximity to a Class II deep injection well, known as the Northstar 1 well. In fact, all of the events were clustered less than a mile around the well.

Northstar 1 is one of 177 operational Class II deep injection wells primarily used for oil and gas fluid waste disposal. (Ohio Disposal Wells) Drilled 200 ft. into the basement rock formation known as the Precambrian layer at a depth of 9,184 (ft), the well began injection in December 2010.

Ohio runs its Class II deep injection program on behalf of the U.S. EPA. As a result, the state meets and in many instances far exceeds U.S. EPA standards and regulations for the program (Comparison Chart). Since the program's inception in 1983, more than 202 million barrels of oilfield fluids have been successfully disposed of, with no reports of subsurface ground water contamination incidents. In addition, no seismic event had been previously linked to operations at any of the state's Class II wells.

The earthquakes and their potential link to the Northstar 1 deep injection well were closely scrutinized by state geologists and regulators, who performed 35 separate inspections of the well from April 26 to Dec. 15, 2011. Each inspection indicated the well was operating within its permitted injection pressure and volume. In addition, ODNR regulators conducted additional testing of the well to determine if injection fluids were entering permitted injection zones. Tracer tests showed injections were reaching appropriate zones and were within permitted injection intervals. However, the tests proved inconclusive with regard to the volume of fluid entering the Precambrian layer. As a result, state regulators requested the well owner plug the Precambrian section of the Northstar 1 borehole, and the well operator voluntarily agreed to the procedure, albeit on a delayed timetable.

With only one seismometer deployed in the Youngstown area, state geologists lacked the necessary data on the earthquakes' depth and exact location to draw a direct correlation between the seismic events and the deep injection well.

Lamont-Doherty Earth Observatory at Columbia University

In November 2011, newly appointed ODNR Director James Zehringer sought to obtain the additional data. After his first briefing on the seismic activity, Director Zehringer ordered the Ohio Geological Survey to seek an outside research partner and deploy the needed portable seismometers around the Youngstown area. The Lamont-Doherty Earth Observatory at Columbia University had the available equipment and was willing to assist the state. The seismometers were deployed on Dec. 1, 2011. (Youngstown Seismic Events)

On Dec. 24, the newly deployed equipment recorded a 2.7-magnitude earthquake in the area. Data from the portable seismometers was downloaded and analyzed by experts at Lamont-Doherty. On Dec. 29, Lamont-Doherty presented ODNR with their preliminary findings, which indicated the seismic event depth was 2,454 ft. below the injection well.

Based on the Lamont-Doherty data, Director Zehringer instructed ODNR regulators to seek the immediate halt of injections at Northstar 1, either voluntarily by the operator or by agency order. At 5 p.m. on Dec. 30, ODNR inspectors witnessed the shut down of the well. (Lamont-Doherty Analysis)

The next day, the Youngstown area experienced a 4.0-magnitude seismic event. Gov. John Kasich immediately placed an indefinite moratorium on three drilled deep injection wells and one well with a permit pending in the vicinity of the Northstar 1 well.

Induced Seismicity

Geologists believe it is very difficult for all conditions to be met to induce seismic events. In fact, all the evidence indicates that properly located Class II injection wells will not cause earthquakes. To induce an earthquake a number of circumstances must be met:

- A fault must already exist within the crystalline basement rock;
- That fault must already be in a near-failure state of stress;
- An injection well must be drilled deep enough and near enough to the fault and have a path of communication to the fault; and
- The injection well must inject a sufficient quantity of fluids at a high enough pressure and for an adequate period of time to cause failure, or movement, along that fault (or system of faults).

A number of coincidental circumstances appear to make a compelling argument for the recent Youngstown-area seismic events to have been induced:

- The Northstar 1 well began injection operations in December 2010. Roughly three months later, the first seismic events were noted and were fairly close to the well;
- Subsequent seismic events were clustered around the vicinity of the wellbore;
- Evidence of permeability zones within the Precambrian basement rock is interpreted in some of the geophysical logs obtained from within the Northstar 1 well; and (Logs A, B, C, D)
- Once sufficient monitoring equipment was in place, the focal depths of events were found to be about 4,000 ft (1,220 m) laterally and 2,500 ft (760 m) vertically from the wellbore terminus.

It appears there are observed permeability zones within the Precambrian basement rock in the "piggyback" logs recorded by the Battelle Memorial Institute during the drilling of Northstar 1.

These logs were not available to inform regulators of possible issues in geological formations prior to well operation. Instead, Battelle produced and made the logs available to provide geologists with additional information on the region's geological formations. In the future, ODNR will require the Class II well owner to provide a suite of geophysical logs germane to the respective injection well.

To establish a better understanding of what may have happened, further analysis and detailed modeling of all factors must be completed on the Northstar 1 well and the surrounding geology. This work is already underway through ODNR and cooperating agencies and institutions.

Deep Injection Well Reforms

Currently, Ohio meets or exceeds all U.S. EPA standards and regulations for Class II deep injection wells. However, the frequency and location of the Youngstown area earthquakes, detailed earthquake depth data provided by Lamont-Doherty, and specific geological information learned about the well site required ODNR to examine its existing Class II deep injection well permitting process and develop a series of changes that will help address seismic activity concerns.

The reforms listed below will make Ohio's Class II deep injection wells among the most carefully monitored and stringently regulated disposal wells in the nation. Ohio will seek the following reforms to its Class II deep injection well program:

- Requires a review of existing geologic data for known faulted areas within the state and avoid the locating of new Class II disposal wells within these areas;
- Requires a complete suite of geophysical logs (including, at a minimum, gamma ray, compensated density-neutron, and resistivity logs) to be run on newly drilled Class II disposal wells. A copy of the completed log, with analytical interpretation will be submitted to ODNR;
- Evaluates the potential for conducting seismic surveys;
- Requires operators to plug back with cement, prior to injection, any well drilled in Precambrian basement rock for testing purposes.
- Requires the submission, at time of permit application, of any information available concerning the existence of known geological faults within a specified distance of the proposed well location, and submission of a plan for monitoring any seismic activity that may occur;
- Requires a measurement or calculation of original downhole reservoir pressure prior to initial injection;
- Requires conducting a step-rate injection test to establish formation parting pressure and injection rates;
- Requires the installation of a continuous pressure monitoring system, with results being electronically available to

ODNR for review;

- Requires the installation of an automatic shut-off system set to operate if the fluid injection pressure exceeds a maximum pressure to be set by ODNR;
- Requires the installation of an electronic data recording system for purposes of tracking all fluids brought by a brine transporter for injection;

To bolster its earthquake monitoring capabilities, ODNR will purchase four additional portable seismometers. These sophisticated monitoring devices will augment existing seismometers where necessary, and provide state geologists with quick access to detailed data on seismic activity. In addition, ODNR is in the process of identifying an "outside" expert with experience in seismicity, induced seismicity, and Class II injection wells to conduct an independent review of the currently available technical information, as well as information to be supplied by the injection well owners in the vicinity of the Northstar 1 well. This independent analysis will provide a scientific third party evaluation and analysis of all technical information to ensure thoroughness of the process.

ODNR is pursuing these changes to deep Cambrian-Precambrian Class II injection wells either through specialized attached permit conditions or through potential changes to either Section 1509 of the Ohio Revised Code or Section 1501:9-03-01 through 1501:9-03-10 of the Ohio Administrative Code. These recommended changes are being proposed to ensure protection of the health and safety of the citizens of Ohio.

PURPOSE AND SCOPE

This preliminary report provides regulatory and geologic context for the Northstar 1 Class II injection well, three nearby Class II injection well facilities under construction, and one pending Class II injection well application. The report examines the initial scientific data pertaining to the potential connection between the Northstar 1 well and 11 seismic events occurring in the Youngstown, Ohio, area between March 17 and Dec. 31, 2011.

The report includes the following:

- Site characterization and geology of the Youngstown area;
- History of Ohio's Class II underground injection well program;
- Permitting, history of drilling operations, and status of the Northstar Class II injection wells;
- A brief history of seismic monitoring in Ohio;
- Preliminary interpretations of data associated with the seismic events in the Youngstown area; and
- Evaluation of data and downhole tests conducted at the Northstar well(s).

Seismicity induced by human activities has been extensively documented. Seismic events have been associated with mining, lake filling, geothermal energy-related injection, oil and gas production activities, and injection disposal wells. Induced seismicity determinations rely upon three primary characteristics of earthquake activity: (1) geographic relationship between the wellbore depth and the location of the earthquake, (2) exceedance of the theoretical friction threshold for fault slippage, and (3) lack of historical seismicity in an area prior to the activity in question (Nicholson and Wesson, 1990). The U.S. EPA (U.S. EPA, in press) developed a series of fundamental questions to evaluate the likelihood of induced seismicity, which includes:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicenters near wells (within five kilometers [km])?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?
6. Are changes in fluid pressure at well bottoms sufficient to induce seismicity?
7. Are changes in fluid pressure at the hypocenter location sufficient to encourage seismicity?

ODNR will continue to collect and evaluate additional scientific data in an ongoing effort to determine the causes of the seismic events and to evaluate potential changes needed to the Underground Injection Control (UIC) program to ensure protection of public health and safety. In an effort to maintain scientific validity to this preliminary report, ODNR has chosen to apply the scientific method to test the hypothesis proposed within this study.

SITE CHARACTERIZATION

Geographic Location

The Northstar 1 well (Mahoning County Permit 23127; APINO 34099231270000) is located in an industrial district of northwestern Youngstown, Mahoning County, Ohio (fig. 1). The well site is on the property of a reclaimed iron foundry, approximately 0.5 miles (mi; 0.8 km) east of Interstate 680 and 0.1 mi (0.2 km) west of the Mahoning River. The U.S. Geological Survey (USGS) Youngstown 7½-minute quadrangle indicates a small, closed, low but relatively flat ground surface with an elevation of approximately 860 feet (ft; 262 meters [m]) at this location. A 10-mile radius, centered on the Northstar 1 well, was chosen as the study area for the maps and discussions throughout this report.

Underground Sources of Drinking Water

The lowest Underground Source of Drinking Water (USDW), as defined (less than 10,000 milligrams per liter [mg/L] total dissolved solids) by the U.S. EPA, near the Northstar 1 injection well site in Mahoning County is the Devonian Berea Sandstone or Pennsylvanian Sharon Sandstone (fig. 2). Based on the work by Vogel (1982), the Berea Sandstone freshwater/saltwater interface extends from southwestern to northeastern Mahoning County, approximately 1 mi (1.6 km) south of the Northstar 1 injection well. North of this line the Berea Sandstone is identified as the deepest USDW, and south of this line the Pennsylvanian Sharon Sandstone is considered the deepest USDW. The complex relationship involving the post-Mississippian unconformity and deep channeling of the Sharon Sandstone make the base of this unit quite variable in this region. Taking a conservative and more cautious approach, the deeper Berea Sandstone would be considered the deepest USDW for this area.

In the study area, the depth to the deepest USDW ranges from about 161 ft to 682 ft (49.1–208 m) below ground surface (bgs). In the Northstar 1 well, the drill depth to the base of the deepest USDW (Berea Sandstone) is 320 ft (97.5 m; table 1) bgs. While the Berea Sandstone is the lowest-defined USDW in the study area, residential water wells in Mahoning County typically produce from shallower Pennsylvanian Sandstone aquifers, glacial deposits, and valley-fill deposits of sand and gravel at depths from 10 ft to 250 ft (76.2 m; Stamm and others, [n.d.]).

Regional Geologic Setting

Northeastern Ohio is situated within the cratonic interior of North America on the northwestern flank of the northern Appalachian Basin (fig. 3). Sediment thickness within the Appalachian Basin varies from a low of around 3,000 ft (914 m) in central Ohio to perhaps more than 45,000 ft (13,716 m) in central Pennsylvania (no wells have been drilled that deep). Western Ohio is dominated by relatively shallow basement rock (Precambrian) with thin, flat-lying sedimentary cover over a series of arches (Cincinnati Arch and Findlay Arch), which were left by the differential subsidence of the surrounding basins more than as a result of tectonic uplift. The eastern half of Ohio has a much greater sediment thickness and number of sedimentary units as a result of longer depositional cycles within the synclinal Appalachian Basin. The eastern portion of the northern Appalachian Basin architecture is thought to have been heavily influenced by the Rome Trough—a set of Cambrian-aged extensional faults and down-dropped blocks (fig. 3) largely oriented northeast–southwest. Large northwest–southeast oriented fault systems cut across the Rome Trough structures and are thought to be of later ages. These fault systems apparently resulted from tectonism of the Taconic and Allegheny orogenies, the latter of which formed the Appalachian Mountains. These events and structures have left this area with a dominant orthogonal structural grain with faults and fractures mostly oriented northeast–southwest or northwest–southeast.

Within the Youngstown area sedimentary rocks are approximately 9,000 ft (2,743 m) thick. The Paleozoic sedimentary strata were deposited upon the Precambrian basement rock, which is composed of igneous and metamorphic rock types. Precambrian basement rock of northeast Ohio have been found to be both igneous and metamorphic and are thought to be an extension of the Grenville Province of such rocks exposed to the north in Canada. Geologic structures, including faults, inherent in the Grenville terrain are thought to be the origin of many faults, general structures, and even stratigraphic changes within the overlying sedimentary strata (fig. 4). Relatively few wells (less than 250) have penetrated this deep in the Precambrian basement rock, especially in eastern Ohio, so knowledge of this surface and the rock types of the Precambrian is fairly limited.

Surficial Materials and Near-Surface Bedrock Geology

The Youngstown area is located in the Killbuck-Glaciated Pittsburgh Plateau section of the Glaciated Allegheny Plateau physiographic province (Ohio Division of Geological Survey, 1998), which is classified as a dissected plateau characterized by a maximum topographic relief of roughly 250 ft. (76 m). The area has been glaciated multiple times; typically the ridge tops and slopes are thinly covered, while thicker accumulations of glacial drift are found in the valleys. Also, the site occurs in the Ohio coalfield, a historic area of extensive coal and clay mining since the early 1800s (Slucher and others, 2006).

In the study area, deposits near the surface are limited to the most recent Wisconsinan ice advance (about 25,000 years ago). Glacial drift varies from less than 5 ft. (1.5 m) on the uplands to more than 150 ft. (46 m) for some of the buried valleys underlying the modern stream valleys (figs. 5 and 6). Glacial drift in the uplands is typically limited to clayey glacial till, commonly ranging from 5 ft. to 40 ft. (1.5–12 m) thick. The uplands feature a number of distinct ridges, formed by underlying resistant sandstone, that influence the local topography and relief. Areas of end moraine also add to the somewhat rolling surface topography, whereas adjacent areas of ground moraine may be relatively flat.

Portions of the valley directly adjacent to both the Mahoning River and adjoining Crab Creek, in the vicinity of downtown Youngstown, contain abundant artificial fill materials (Angle, 2003; Shrake and others, 2006). Water well log records indicate up to 40 ft (12 m) of bricks, demolition debris, slag and cinders from the steel industry, and spoils and overburden from nearby strip mines and quarries. These materials may be prone to differential subsidence.

Surface and near-surface bedrock underlying the Youngstown study area belongs to the Mississippian and Pennsylvanian Systems (figs. 7 and 2). Outcrops of Mississippian-age rocks are limited to exposures near stream level where major tributaries join the Mahoning River in northeastern Mahoning County. The area features many exposures of Pennsylvanian System bedrock, particularly along valley sides and in strip mines and quarries.

Rocks of the Mississippian System underlie the floors of the deeper buried valleys and are exposed along the Mahoning River in the vicinity of Youngstown (Cummins, 1950). These rocks are interbedded, fine-grained sandstones, siltstones, and shales of the Cuyahoga Formation (Cummins, 1950).

The contact between rocks of the Mississippian System and the Pennsylvanian System is a major disconformity that represents a large interval of erosion. The elevation and nature of the contact is highly variable. Cummins (1950) mentions an elevation difference of the contact exceeding 100 ft (30 m) in northeastern Mahoning County, suggesting the differential nature of erosion and downcutting during the Pennsylvanian.

Rocks of the Pennsylvanian System include formations of both the Pottsville Group and the Allegheny Group. The Pottsville Group is represented primarily by interbedded shales, dirty sandstones, and siltstones along with thin but important coals, underclays, and limestones. Some of the shales contain nodular bands of iron ore that had great local economic significance in the nineteenth century. The basal formation is the Sharon Sandstone (conglomerate)—a thick, massive, coarse-grained sandstone containing conglomeratic zones comprised of bands of milky-white, rounded quartzite pebbles. The Massillon Sandstone is a very resistant unit that caps many of the steep ridges in the Youngstown study area and is underlain by the Sharon No. 1 coal seam and the Sharon shale. In many locales, the Sharon shale may be absent due to erosion. Typically, the Sharon Sandstone directly overlies the Cuyahoga Formation. The Allegheny Group contains interbedded sandstones, siltstones, shales, clay, coal, and thin limestones.

Mining Activity

Historically, the Sharon No. 1 coal seam (fig. 2) was of great importance to the local economy of the Youngstown area. Ohio Geological Survey records indicate 52 abandoned underground mines (AUMs) within the Youngstown study area, ranging in date from 1868 to 1945 (fig. 8). Presumably, all of these mined from the Sharon coal. There also are numerous small mine openings, access shafts, and adits that lack known mine maps. These mines and peripheral features are related to a long history of subsidence and other related problems within the area, many of which have been documented by Professor Ann Harris of the Department of Geological and Environmental Sciences at Youngstown State University.

Surface mining also has been prevalent in the Youngstown study area, with numerous strip mines and quarries present. The Sharon No. 1 coal seam and perhaps the Quakertown No. 2 coal primarily were the mined units.

Some limited mining of clay and shale and, in areas where sufficiently thick, the Vanport limestone occurred as well. Historically, the Sharon Sandstone was quarried in the area and used for aggregate or as a source of abrasives.

Ohio Geological Survey records show that there was no active reported surface or underground mining in the Youngstown study area for calendar year 2010 (Wolfe, 2011). Mining in Mahoning County was limited mostly to the southeastern corner of the county.

Oil and Gas Activity

Ohio has a long history of oil and gas production, extending back to 1860. Since that year, more than 1,000 oil and gas fields have been discovered (fig. 9) and more than 250,000 wells drilled. The oil and gas production within and adjacent to the 10-mi (16-km) study area is from fields completed in the Upper Devonian Berea and Cussewego Sandstones, the Lower Devonian Oriskany Sandstone, and the Lower Silurian Clinton Sandstone. (See figure 10 for the locations of oil and gas fields producing from these formations within and adjacent to the study area.) The earliest oil and gas production in the area originated from the Berea Sandstone in the New Middleton Field, discovered in 1910. The productive Berea in this field lies at an average depth of 580 ft (177 m) bgs. The most widespread producing formation in the area is the Clinton Sandstone, which is productive in the North Ellsworth Consolidated Field to the west and the Hartford Field to the northeast. The depth to

Clinton reservoirs across the area averages about 4,840 ft (1,475 m) bgs. Clinton reservoirs were first produced in the area in 1949. The most recent oil and gas discovery in the area is the Youngstown Field, which first produced in 1999 from the Oriskany Sandstone at an average depth of 3,360 ft (1,024 m) bgs.

According to ODNR records, a total of 2,075 oil and gas wells have been drilled within the 10-mi study area, starting in 1916 (fig. 11). Of those wells, a total of 163 directional wells are reported to have been drilled within the 10-mi study area, starting in 1991. For all wells, total drilled depths range from 33 ft to 9,192 ft (10–2,802 m). A total of 1,645 wells have been drilled to the Clinton Sandstone. Nineteen wells reported comingled production from both the Clinton and the Oriskany Sandstone. Only two oil and gas wells had been drilled to the Knox Dolomite or deeper (fig. 11). Recently, five deep wells have been drilled for the purposes of saltwater injection. The Northstar 1 is the only one of these that injected oilfield wastes; the other permits currently are on hold.

Geologic Structure

In general, the bedrock units of the Youngstown area dip gently to the southeast at a rate of up to about 50 ft per mi (9.4 m/km) into the Appalachian Basin. No large folding is known within the area. The closest known fault system is the Smith Township Fault, a northwest–southeast oriented fault with the upthrown side to the northeast, in southeastern Mahoning County (figs. 4 and 12). This fault can be mapped on multiple horizons from the Precambrian surface through the Berea Sandstone and above, illustrating that it has had recurrent movement throughout geologic time.

A number of geologists have noted the Mahoning River Valley as a geologic lineament (a straight-line topographic feature) that may be related to faulting, as rivers tend to follow zones of weakness, such as those set up in fault or fracture zones. Mason (1999) noted the Mahoning River Valley as part of a large feature he named the Blairsville-Broadtop Lineament. After using available well control to map structure on three widely separated geologic horizons—the Dayton Formation, Onondaga Limestone, and Berea Sandstone—the Ohio Geological Survey does not find evidence of offset along a fault in this location. Thus if a deep-seated fault is present at this location, it must have had very little vertical movement associated with it; lateral movement only along faults is possible. A cross section through the Northstar 1 well and across the Mahoning River Valley illustrates some minor thickness changes across this area but does not show strong evidence of faulting (fig. 13).

"Piggyback" Logging

Geoscientists with Battelle Memorial Institute have been researching the deep geology of Ohio and neighboring states since 1999, characterizing the region's ability for geologic sequestration of carbon dioxide. Beginning in 2004, Battelle started using the concept of "piggyback" drilling and/or logging to obtain additional geologic and engineering data from deep wells in the area (Gupta, 2009). Using the piggyback concept, Battelle enters into an agreement with oil and gas companies that have permitted deep-exploration wells in areas where little or no prior deep drilling has been conducted. Battelle then uses research funding, provided through the U.S. Department of Energy and/or the Ohio Coal Development Office, to obtain much more comprehensive geophysical log suites from the borehole than the operator normally would obtain. In some cases, Battelle has paid to deepen the hole further than the operator would have. Battelle also has paid to obtain full-diameter or sidewall core samples from the wells for use in further analyses. The Ohio Geological Survey has been a research partner with Battelle on a number of projects where piggyback drilling was involved. In 2007, Battelle and the Ohio Geological Survey partnered to drill a state-funded deep test well in Tuscarawas County, using funding provided through the Ohio Coal Development Office (Wickstrom and others, 2010).

Prior to drilling of the Northstar 1 well (APINO 3409923127) in May 2010, D & L Energy Inc., contacted the Ohio Geological Survey for assistance in forecasting formation tops to be encountered while drilling. The Ohio Geological Survey then alerted Battelle to the proposed Northstar 1 well as a candidate for the piggyback program. Prior to the drilling of the Northstar 1 well, the nearest Precambrian basement test was many miles away in any direction (fig. 14). Thus, information from this well was deemed important in furthering our understanding of the deep geology of eastern Ohio. Unfortunately, at the time of drilling, very little funding was available to the piggyback program. Sufficient funds were available to enable a fairly comprehensive log suite to be gathered from the well; however, funds to pay for all processing of the log information were not available at that time. Final processing of log data was obtained by Battelle in late March 2011. (See table 2 for the types of logs acquired on this well and their respective depth intervals. Copies of all logs are available from the Ohio Geological Survey.)

[1]Most drillers refer to this as the Mt. Simon Sandstone.

INJECTION INTERVAL AND ADJACENT STRATA

Table 1 and figure 15 illustrate the general sequence of geologic units and their thickness found beneath Youngstown as revealed by the drilling of the Northstar 1 well. The Northstar 1 well was drilled into Precambrian granite for a total depth of 9,192 ft (2,802 m). Following evaluation of open-hole geophysical well logs, production casing was cemented in at a depth of 8,215 ft (2,504 m). The well was then completed open-hole from 8,215 ft to total depth (9,192 ft). Potential reservoirs noted from the initial geophysical logs include the Copper Ridge "B-zone" and Conasauga basal unnamed sandstones. Open-hole electric logs were used to calculate all reservoir porosity that was greater than 8 percent. The two largest porosity zones within the well are the Copper Ridge dolomite "B-zone," with a total of 32 net ft (9.8 m) averaging 9.4 percent porosity, and the Conasauga Group unnamed basal sandstone, which showed 48 net ft (15 m) averaging 10.3 percent porosity. (See fig. 16 [a, b, c] for select geophysical-log plots for the entire open-hole section of the well.)

Above the open-hole interval and behind production casing, the Beekmantown dolomite and Rose Run Sandstone intervals of the Knox Dolomite Group appeared tight and were considered nonreservoir. Approximately 3,000 ft (914 m) of tight carbonates and shale were noted above the open-hole injection zone and beneath the Silurian Clinton Sandstone, the unit to which most previous oil and gas wells had been drilled in the area.

Information presented in this report focuses on the lowermost geologic units within the Northstar 1 well, which were the injection horizons and immediate confining strata: the Precambrian; the Cambrian Conasauga Group (Maryville Formation and basal unnamed Sandstone); Knox Dolomite (Copper Ridge dolomite, Rose Run Sandstone, and Beekmantown dolomite); and Ordovician Wells Creek Formation and Black River Group/Trenton Limestone (fig. 15).[2] The basal unnamed sandstone of the Conasauga Group and portions of the Knox Dolomite/Copper Ridge are considered the reservoirs for brine injection at the site.

Precambrian

As briefly discussed prior, the Precambrian strata in eastern Ohio are part of the Grenville Province of igneous and metamorphic rocks. Within the Northstar 1 well the Precambrian was encountered from a depth of 8,992 ft (2,741 m) through total depth of 9,192 ft (2,802 m; 200 ft [61 m] penetrated). Just above and at the Precambrian surface, porosity and permeability zones are indicated on the logs from 8,976 ft to 8,996 ft (2,736–2,742 m; fig. 16c and 17). These porosity zones may be due to some weathering of the Precambrian surface, the deposition of larger grained "rubble" on this unconformity surface, or diagenetic altering of the rock by fluids moving along this surface over millions of years.

The upper portion of the Precambrian (~9,005–9,070 ft [2,745–2,765 m]) is almost entirely black and consists primarily (greater than 50 percent) of biotite, with lesser amounts of quartz, amphibole, feldspar, and undetermined trace minerals. This entire zone also displays higher than normal density readings (±2.85 grams/cubic centimeter [g/cc]; fig. 16c). The lowermost portion of the Precambrian encountered within the well has a more normal granitic composition featuring a high percentage of quartz and feldspar, with minor biotite and lesser accessory minerals. Log characteristics are consistent with granitic rock (density about 2.6–2.65 g/cc). The magnetic resonance log (fig. 16c), which can detect higher and lower permeability zones of the rocks, shows a high permeability zone (greater than 2 darcys [d]) with a high percentage of moveable fluid immediately below the upper high-density, biotite-rich section from 9,070 ft to 9,086 ft (2,765–2,769 m). Thus far, there is no apparent reason for this permeability zone on the geophysical logs; and at this time we cannot rule out that this permeability reading may be false or related to a rather exotic lithologic change. Another high-permeability zone with a high percentage of moveable water is found from 9,097 ft through 9,106 ft (2,773–2,776 m; fig. 16c). At this same depth on the imaging logs, high-angle fractures are interpreted (fig. 17). The Precambrian of this well warrants additional analyses as it is still not fully understood from the limited samples recovered and the log analyses performed. X-ray diffraction is being performed on samples to provide distinct mineralogical components. Further log analyses and log processing also are being pursued.

Conasauga Group

The Conasauga Group consists of three units in ascending order: Maryville, Nolichucky, and Maynardville Formations (fig. 15; Baranoski, in press). The Nolichucky and Maynardville are poorly developed and thin north of the Smith Township and Highlandtown fault systems (fig. 4). Total thickness of the group ranges from zero at pinch-out in western and northern Ohio to more than 700 ft (213 m) in eastern and southern Ohio. Thickness of the Conasauga increases to more than 3,000 ft (914 m) in the Rome Trough.

[2]The Cambrian stratigraphy follows that from Baranoski (in press).

Maryville Formation

The Maryville Formation lies unconformably on the Precambrian Grenville basement complex and consists of a lower portion of interbedded sandstone and dolostone and an upper portion consisting dominantly of dolostone. The lower sandstone-rich portion grades upward into dominantly dolostones of the upper Maryville, which are light to medium gray and pinkish gray, cryptocrystalline to fine- and medium-crystalline and arenaceous dolostone. The total thickness of the unit is about 596 ft (182 m) in the Northstar 1 well (8,396–8,992 ft [2,559–2741 m]), while the upper dolostone-dominant portion of the Maryville is 466 ft thick (8,396–8,862 ft [2,559–2,701 m]) with scattered sandy breaks and permeability zones (fig. 16b).

The basal sandstone portion of the Maryville Formation is commonly referred to as the Mt. Simon Sandstone. The Mt. Simon Sandstone is the basal sedimentary unit in western Ohio, but recent work by the Ohio Geological Survey (Baranoski, in press) has shown these two intervals are not equivalent. The lower portion consists of interbedded quartz arenite (sandstone), dolostone, and minor amounts of shale. The quartz arenite is white to light gray and pinkish gray, fine- to medium-grained, and moderately to well-sorted, sub-rounded to angular grains.

The basal sandstone portion is approximately 130 ft (40 m) thick in the Northstar 1 well (8,862–8,992 ft [2,701–2,741 m]). These unnamed basal sandstones have numerous 2-ft to 10-ft (0.6–3.0 m) thick potential reservoirs. The unit contains 48 ft (15 m) of sandstone porosity reading greater than 8 percent on the logs, with 10.3 percent average porosity (fig. 16c). The magnetic resonance log indicates possible high-permeability zones within this interval that in part correlate to the porosity zones. The lower-permeability areas within greater than 8 percent porosity cutoff may be due to diagenesis of pore throats or lack of lithologic processing.

Nolichucky and Maynardville Formations

In northeastern and eastern Ohio the Nolichucky and Maynardville Formations are thin and difficult to separate from the overlying Knox Dolomite. The Nolichucky Formation consists of dominantly medium-brown to dark-brown, fossiliferous shale and dolomite interbedded with lesser amounts of siltstone and quartz arenite, which is typical for southern Ohio. The upper contact is gradational to sharp with the dolomitic limestones of the Maynardville Formation. The Maynardville Formation consists of interbedded shaley dolomite with lesser amounts of limestone, dolomite, siltstone, and quartz arenite. These units are not subdivided at the Northstar 1 well site. Combined thickness of the units is approximately 30 ft (9 m) in the well (8,366–8,396 ft [2,550–2,559 m]; fig. 16a).

Knox Dolomite

The Knox Dolomite consists predominantly of finely crystalline, vuggy dolomite with localized thin beds of fine-grained, arkosic, dolomitic sandstone and siltstone and small amounts of anhydrite. The top of the Knox is a major regional angular unconformity surface, along which karst topography is commonly found. The Knox is subdivided into three units which subcrop along the Knox unconformity in the eastern half of the state; they are, in ascending order: the Copper Ridge dolomite, Rose Run Sandstone, and Beekmantown dolomite (Janssens, 1973; fig. 18). Other less-extensive and locally productive units within the Knox Group include the Krysik Sandstone (of northern Ohio) and the more extensively deposited "B-zone" (of central and eastern Ohio). Thickness of the Knox ranges from less than 100 ft (30 m) in Ottawa County to more than 1,500 ft (460 m) in southern Ohio. In the Northstar 1 well the Knox Dolomite and subunits are 680 ft (207 m) thick (7,686–8,366 ft [2,343–2,550 m]).

Copper Ridge dolomite

The Copper Ridge dolomite ("Trempealeau" of drillers) consists of a lower, darker, crystalline, arenaceous, vuggy dolomite and an upper, light-brown, crystalline, vuggy dolomite. An interval separating the upper and lower Copper Ridge is informally called the "B-zone" (Calvert, 1974), which is characterized by distinctive thin, clastic-rich intervals of dolomitic, glauconitic, argillaceous, fine-grained sandstone and siltstone. Thickness of the Copper Ridge varies from 1,100 ft (335 m) in southern Ohio to approximately 40 ft (12 m) in northern Ohio, where the unit has been eroded at the Knox unconformity. The Copper Ridge is 400 ft (122 m) thick in the Northstar 1 well (7,966–8,366 ft [2,428–2,550 m]). The "B-zone" is approximately 166 ft (50.5 m) thick in the well (8,132–8,298 ft [2,479–2,529 m]) and contains potential reservoirs, including a well-developed interval from 8,225 ft to 8,248 ft (2,507–2,514 m) and several beds of one to two feet in thickness. Approximately 32 ft (9.8 m) of net porosity greater than 8 percent exists in the unit, with 9.4 percent as the average porosity (fig. 16a).

Rose Run Sandstone

The Rose Run Sandstone consists of laminated to cross-bedded, interbedded fine- to coarse-grained, dolomitic, arkosic sandstone and dolomite (Janssens, 1973; Riley and others, 1993). The Rose Run is generally considered the top of the Upper Cambrian strata (Ryder, 1992; Riley and others, 1993) and it occurs throughout eastern Ohio and adjacent areas of Kentucky, Pennsylvania, and West Virginia (fig. 18). Up to five beds of sandstone interbedded with dolomite occur in eastern Ohio (Riley and others, 2002). The top of the Rose Run is gradational with the overlying Beekmantown dolomite, where present, or has a sharp erosional contact at the Knox unconformity. Thickness of the Rose Run varies from 125 ft (38.1 m) in eastern Ohio to zero ft where the unit has been eroded at the subcrop or where the Rose Run changes laterally westward into dolomite in southwestern Ohio. Net thickness of the sandstone is related to depositional environment and subsequent erosion at the Knox unconformity surface. The Rose Run is 104 ft (31.7 m) thick in the Northstar 1 well (7,862–7,966 ft [2,396–2,428 m]) but does not appear to contain significant porosity zones.

Beekmantown dolomite

The Beekmantown dolomite consists of massive-bedded, microcrystalline to crystalline dolostone, which may contain desiccation features and small amounts of anhydrite, and is locally vuggy (Janssens, 1973; and Riley and others, 1993). The Beekmantown forms an extensive, regional subcrop in southern and eastern Ohio, extending into Kentucky (fig. 18; Riley and others, 1993). Where present, the top of the Beekmantown forms a sharp erosional contact with Ordovician units overlying the Knox unconformity. In some areas of eastern Ohio, the Beekmantown caps the Rose Run as outlying monadnocks. Thickness of the Beekmantown ranges from more than 600 ft (183 m) in eastern Ohio to zero ft at the subcrop, where the unit has been eroded at the Knox unconformity. The Beekmantown is 176 ft (53.6 m) thick in the Northstar 1 well (7,686–7,862 ft [2,343–2,396 m]) and does not appear to be porous, instead forming the initial cap rock for the injection zone.

HISTORY OF THE UIC PROGRAM

Each year, Americans generate hundreds of billions of gallons of hazardous and nonhazardous wastes that must be safely managed to protect public health and safety.

In 1974, Congress passed the Safe Drinking Water Act, authorizing the U.S. EPA to develop minimum federal requirements for injection practices designed to prevent contamination of USDWs, which are defined as aquifers or portions of aquifers that have a sufficient quantity of ground water to supply a public water system or contain fewer than 10,000 mg/L of total dissolved solids (U.S. EPA, 2001). The U.S. EPA UIC Program establishes minimum requirements for five classes of injection wells based upon the nature of the injected waste stream. States and tribes may apply to the U.S. EPA to obtain primary enforcement responsibility, or primacy, to permit and regulate injection wells within the boundaries of their jurisdictional authority (U.S. EPA, 2001). In order for a state to receive primacy, the state program must meet the minimum federal requirements but may be more stringent than requirements established by U.S. EPA regulations.

Class II injection wells are exclusively limited to the injection of fluids produced from the drilling, stimulation, or production of oil and natural gas wells. ODNR's Division of Oil and Gas Resources Management (DOGRM) applied for and received primacy of its Class II injection well program from U.S. EPA on Aug. 23, 1983, and it became effective on Sept. 22, 1983, pursuant to Section 1425, P.L. 96-502. The U.S EPA, Region V in Chicago oversees and audits Ohio's Class II injection well program pursuant to the primacy agreement. Specific Ohio laws and rules for the Class II injection wells are in Sections 1509 of the Ohio Revised Code (primary sections 1509.21–1509.226) and under Section 1501:9-3 of the Ohio Administrative Code (primary sections 1501:9-3-01 through 1501:9-3-10). Many of the Ohio standards regarding Class II injection wells are more stringent than U.S. EPA regulatory standards. (See table 3 for specific areas where Ohio's Class II injection regulations are more stringent than U.S. EPA regulations.)

The DOGRM has implemented and maintains an effective Class II injection well program. Since 1983, more than 202 million barrels (42 gallons per barrel) of oilfield fluids have been injected back into depleted oil and gas reservoirs or deep geologic formations that naturally contain highly saline water. From 1983 to present, no subsurface ground-water contamination incidents have been caused by Class II injection. Furthermore, since 1983, no seismic event has been linked to operations at any Class II injection well in Ohio.

Since 1983, the number of active Class II injection wells in Ohio has increased and declined based upon supply-and-demand requirements within the oil and natural gas industries. Ohio currently has 194 Class II injection wells permitted in 41 counties. Eighty-five percent of Class II injection wells (165) are permitted to inject produced fluids into zones that are above the Mt. Simon Sandstone. There are 29 Class II injection wells that have been permitted to inject oilfield fluids into multiple zones, which include the Mt. Simon Sandstone, the lowest sedimentary formation in Ohio, directly above the Precambrian basement. With the recent development of the Marcellus Shale and now, the Utica Shale play in the Appalachian Basin, the demand for Class II injection wells has increased in Ohio. In 2011, DOGRM issued 29 new Class II permits for Ohio and currently there are 13 new Class II injection applications pending. Of the 194 Class II injection wells permitted in Ohio, 177 of them are in operation (fig. 19).

Ohio has always received out-of-state oilfield fluid wastes for disposal and has experienced significantly increased quantities with the new shale plays. The increasing oilfield fluid waste disposal in Ohio originating from other transporting states has raised the question of whether Ohio can limit or prohibit the disposal of out-of-state oilfield fluid wastes. The U.S. Constitution under the Dormant Commerce Clause (within the Interstate Commerce Clause) prohibits states from interfering with shipments (such as oilfield fluid wastes) of commerce from adjoining states.

New York and Pennsylvania have a very limited number of Class II injection wells, and neither state has primacy of its UIC Program. U.S. EPA Region II and Region III regulate the New York and Pennsylvania Class II programs, respectively. Prior to 2011, the common method for disposal for oilfield fluid wastes in New York and Pennsylvania has been treatment and surface release at brine treatment plants subject to the National Pollutant Discharge Elimination System (NPDES) permits issued pursuant to the Federal Clean Water Act.

In May 2011, due to increased public outcry and potential contamination issues, the governor of Pennsylvania prohibited these brine treatment plants from accepting any more fluids generated during the hydraulic fracturing flowback process from Marcellus Shale wells. This eliminated the main disposal method in Pennsylvania and caused a dramatic increase in demand for Class II disposal operations in Ohio.

Nationally, there are 144,000 Class II injection wells disposing of in excess of 2 billion gallons of oilfield wastes each day (U.S. EPA, [n.d.]). Ohio's current Class II total rate of disposal is less than 1 percent of the nation's total. Class II injection remains the proper and environmentally safe method of disposal of oilfield fluid wastes.

HISTORY OF THE NORTHSTAR INJECTION WELLS

The following is a history of the four wells and one application owned by Northstar Disposal Services, LLC. Northstar 3 LLC and D & L Energy Inc., were issued four permits to install Class II injection wells in the Youngstown area. The Northstar 1 well is the only well that is completed and approved by the DOGRM for operations. Three other wells (Northstar United 2, Northstar Khalil 3, and Northstar Collins 6) have been drilled, and surface-storage and pumping facilities are under construction. D & L Energy Inc., also has applied for a permit to drill the Northstar Nexlev 5 injection well. The DOGRM has placed all four injection wells and the one application on hold pending the final analysis of local seismic activities.

Northstar 1 (SWIW 10), Permit 34-099-23127-00-00, Mahoning County, Youngstown Township[3]

- D & L Energy Inc., filed an application to drill the Northstar 1 well with the DOGRM on March 2, 2010. The initial application was to "Drill New Well" with the intent of testing the geologic formations for potential injection as a Class II injection well. The proposed injection formations to be tested were the Trenton through Mt. Simon with a proposed total depth of 10,000 ft (3,048 m; Appendix 3).
- Permit 34-099-23127-00-00 was issued on March 22, 2010, to D & L Energy Inc., (Appendix 4).
- Drilling commenced on March 27, 2010, and a total depth of 9,184 ft (2,799 m) was reached on April 13, 2010. (Appendix 5).
- D & L Energy Inc., applied to convert permit 34-099-23127-00-00 to a Class II disposal well on June 10, 2010 (Appendix 6).
- The required public notice was run in the Youngstown Vindicator newspaper on June 24, 2010. The DOGRM did not receive any objections to the application (Appendix 7).
- The permit was issued on July 12, 2010 (Appendix 8).
- The maximum allowable surface injection pressure was set for the Northstar 1 well at 1,890 pounds per square inch (psi) based upon the formula within Ohio Administrative Code Section 1501:9-3-07 (D). This is a very conservative method for calculating maximum allowable surface injection pressure. After the permit is issued and the well is injecting, the operator can request a modification to the injection pressure based upon the actual specific gravity of the injection fluid. A composite sample of the injection fluid is sampled by the operator and sent to a lab for analysis. That lab analysis is sent to DOGRM for review and adjustment of the maximum allowable surface injection pressure based upon the actual specific gravity of the injection fluid.
- On Aug. 24, 2010, D & L Energy Inc., requested to transfer the Northstar 1 well to Northstar Disposal Services, LLC. The transfer was processed on Sept. 9, 2010 (Appendix 9).
- The injection facility was complete and the first injection commenced on Dec. 22, 2010.
- On March 14, 2011, D & L Energy Inc., (principal of Northstar Disposal Services, LLC) requested an increase in the maximum allowable surface injection pressure from the initial approved 1,890 psi to 2,250 psi. D & L Energy Inc., provided the DOGRM with a laboratory analysis of the specific gravity of the fluid being injected as a basis for their request. Based on the actual specific gravity of the fluids being injected, Chief's Order 2011 13, issued on March 16, 2011, granted the increase in maximum allowable surface injection pressure. Approved pressure did not rise above 1890 psi until March 19, 2011. (Appendix 10).
- On May 3, 2011, D & L Energy Inc., requested a second increase of the maximum allowable surface-injection pressure.

[3]The current owner of this well is Northstar Disposal Services, LLC.
[4]Current owner of the well is D & L Energy Inc.

- D & L Energy Inc., provided the DOGRM with a laboratory analysis of the fluid being injected as a basis for their request. Based on the specific gravity of the fluid being injected, Chief's Order 2011-15 was issued on May 3, 2011, granting the increase in maximum allowable surface injection pressure to 2,500 psi (Appendix 11).
- As of Dec. 31, 2011, 495,622 barrels of fluid have been injected into the Northstar 1 well. Monthly injection volumes pump run times and injection pressures are included in Appendix 12 and 13.
- On Dec. 30, 2011, ODNR Director James Zehringer requested D & L Energy Inc., cease injection at the well. D & L Energy Inc., voluntarily shut down the Northstar 1 injection well on Dec. 30, 2011.

From April 26 through Dec. 15, 2011, the DOGRM inspected the Northstar 1 well on 35 occasions. (See table 4 for the number of inspections performed by the DOGRM, by general purpose.)

Northstar United 2 (SWIW 17), Permit 34-155-24043-00-00, Trumbull County, Liberty Township[4]

- D & L Energy Inc., filed an application with the DOGRM to drill the Northstar United 2 well as a Class II injection well on May 24, 2011. The proposed injection formations were the Knox through Precambrian with a proposed total depth of 9,300 ft (2,835 m; Appendix 14).
- The required public notice was run in the Youngstown Vindicator newspaper on June 10, 2011; no objections received (Appendix 15).
- Permit 34-155-24043-00-00 was issued to D & L Energy Inc., on June 28, 2011 (Appendix 16).
- Drilling commenced on June 21, 2011, and total depth of 9,038 ft (2,755 m) was reached on Aug. 21, 2011 (Appendix 17).
- Current status: Surface facility under construction.
- No injection has occurred at this location.

Northstar Khalil 3 (SWIW 11), Permit 34-099-23157-00-00, Mahoning County, Coitsville Township[5]

- D & L Energy Inc., applied through the DOGRM to drill the Northstar Khalil 3 well as a Class II injection well on May 24, 2011. The proposed injection formations were Knox through Precambrian with a proposed total depth of 9,300 ft (2,835 m; Appendix 18).
- The public notice was run in the Youngstown Vindicator newspaper on June 10, 2011. The DOGRM did not receive any objections (Appendix 19).
- Permit 34-099-23157-00-00 was issued to D & L Energy Inc., on June 27, 2011 (Appendix 20).
- Drilling commenced on Aug. 18, 2011, and total depth of 9,581 ft (2,920 m) was reached on Oct. 5, 2011.
- On Nov. 9, 2011, D & L Energy Inc., requested to transfer permit 34-099-23157-00-00 to Northstar 3 LLC. The transfer of this permit to Northstar 3 LLC occurred on Nov. 30, 2011 (Appendix 21).
- Current status: Surface facility under construction.
- No injection has occurred at this location.

Northstar Collins 6 (SWIW 13), Permit 34-099-23171-00-00, Mahoning County, Coitsville Township[6]

- D & L Energy Inc., applied with the DOGRM to drill the Northstar Collins 6 well as a Class II injection well on Sept. 6, 2011. The proposed injection formations were Knox through Mt Simon Sandstone with a proposed total depth of 9,900 ft (3,017 m; Appendix 22).
- The required public notice was run in the Youngstown Vindicator newspaper on Oct. 22, 2011; no objections received (Appendix 23).
- Permit 34-099-23171-00-00 was issued on Nov. 10, 2011 (Appendix 24).
- Drilling commenced on Nov. 11, 2011, and total depth of 9,798 ft (2,986 m) was reached on Nov. 30, 2011
- (Appendix 25).
- Current status: Surface facility under construction.
- No injection has occurred at this location.

Northstar Nexlev 5 (SWIW 20), Application aAMY0000420, Trumbull County, Hubbard Township

- D & L Energy Inc., applied with the DOGRM to drill the Northstar Nexlev 6 well as a saltwater injection well on Dec. 29, 2011. The proposed injection formations were the Knox through the Mt. Simon Sandstone with a proposed total depth of 9,300 ft (2,835 m; Appendix 26).
- The required public notice was run in the Youngstown Vindicator newspaper on Oct. 27, 2011 (Appendix 27).
- Objections to the application were submitted to the DOGRM by the Hubbard Township Trustees on Oct. 19 and Dec. 13, 2011 (Appendix 28).
- A public meeting was held on Dec. 13, 2011, to address the relevancy of the objections to the application.

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[5] Current owner of the well is Northstar 3 LLC.
[6] Current owner of the well is D & L Energy Inc.

- Permit number 34-155-24050-00-00 was assigned to this application on Dec. 29, 2011, but the permit has not been issued.
- This permit remains on hold until a full analysis of the seismic activities in the vicinity of the Northstar 1 well is complete.

MEETINGS AND DISCUSSIONS

On Sept. 30, 2011, ODNR and representatives of Battelle met to discuss the seismic activity near the Northstar 1 injection well in Youngstown, Ohio. Decisions were made to require D & L Energy Inc., to run tracer and spinner surveys on the Northstar 1 injection well to determine if injection fluids were entering the permitted injection zones. The tracer survey uses beads that are injected into the well and go out into the geological formations that are capable of taking fluids. After the beads have been injected, a gamma ray geophysical log is run to determine which zones took the fluids. The spinner survey also is a tool used to track fluid injection routes and locations. Additionally, it was determined that the Precambrian section of the Northstar 1 borehole would need to be plugged off with cement. D & L Energy Inc. was notified by telephone and email to immediately schedule the tracer and spinner survey tests.

On Nov. 21, 2011, newly appointed ODNR Director James Zehringer received his first briefing on Youngstown area seismic activity. He immediately ordered the Ohio Geological Survey to deploy portable seismometers around the Youngstown area. The Lamont-Doherty Earth Observatory at Columbia University was contacted and found to have available equipment, which were subsequently deployed on Dec. 1, 2011.

On the afternoon of Dec. 29, Lamont-Doherty provided ODNR with a preliminary analysis of the 2.7-magnitude Dec. 24 earthquake. The data indicated the seismic event depth was within the reach of the Northstar 1 injection well. Based on this analysis, Director Zehringer instructed DOGRM to seek the immediate halt of all activity at Northstar 1, either voluntarily by the operator or by agency order. The operator agreed to a voluntary halt. At 5 p.m. on Dec. 30, ODNR inspectors witnessed the halt of all injections and de-pressurization of the well.

On Dec. 31, Youngstown experienced a 4.0-magnitude seismic event. After a briefing from Director Zehringer and key ODNR staff, Gov. John Kasich placed an indefinite moratorium on Northstar 1, as well as four other permitted and/or drilled wells in the immediate area. Legislative leaders and key stakeholders were also advised of the administration's course of action. After initial outreach was completed, Director Zehringer and key ODNR staff hosted a media conference call to provide the public information on the seismic event and announce immediate actions taken.

On Jan. 4, 2012, DOGRM staff met with representatives of D & L Energy Inc., and Northstar 3 LLC to discuss expectations by the ODNR for the two entities owning the Northstar 1 well, as well as the three other drilled Class II injection wells (not yet in operation) and the one pending Class II injection permit application. The DOGRM requested the two companies prepare a plan for each well that would include:

- Identification of existing data that would assist in the evaluation of the recent seismic events;
- Identification of new data to be collected to assist in the evaluation;
- Options for plugging back the wells that had been drilled;
- Reductions to injection pressures and/or volumes to be injected;
- Conducting downhole pressure monitoring to obtain original reservoir pressures;
- Review of existing geologic data available at the Ohio Geological Survey; and
- Obtaining or conducting seismic surveys in an effort to identify potential faults within the vicinity of the five Class II injection well locations.

ODNR would then review the proposed plans for addressing the seismic events and correction actions needed to be undertaken to ensure public health and safety. ODNR is currently awaiting the proposed plans from the companies.

- On Jan. 9, 2012, representatives from the Ohio Legislature and the media met with ODNR representatives to get an update on the seismic events around Youngstown through presentations by the Ohio Geological Survey and the DOGRM on the seismic events, geology of the area, and Class II injection well regulations. A question-and-answer period took place afterwards along with a tour of the Horace R. Collins Core Repository and the Ohio Seismic Network (OhioSeis).
- At the request of State Rep. Robert F. Hagan and local Youngstown officials, ODNR participated in a public meeting held at the Covelli Center in Youngstown, Ohio, on Jan. 11, 2012. Presentations were given by ODNR; Dr. Jeffrey Dick, Youngstown State University Geology Department; Bill Kinney, representing the oil and gas industry; and Jack Shaner, Ohio Environmental Council. A question-and-answer period followed the presentations.

- On Jan. 12, 2012, ODNR met with representatives of the Ohio oil and gas industry to present scientific information regarding the Northstar 1 Class II injection well and the seismic events in the Youngstown area. Discussions included potential changes in Class II injection well requirements, and suggestions were addressed during this meeting.

TESTING CONDUCTED ON THE NORTHSTAR 1 WELL, PERMIT NUMBER 34-099-23127-00-00

On June 4, 2010, a 48-hour injectivity test was performed on this well to try and determine formation parting pressure. Appalachian Well Service was on-site to conduct the test, which was witnessed by DOGRM personnel. Pursuant to Section 1501:9 3 06(A) of the Ohio Administrative Code, D & L Energy Inc., requested a 48-hour injectivity test to evaluate potential injection zones. The request was granted by the DOGRM. Appalachian Well Service began pumping brine at a rate of one barrel per minute (bpm) and gradually increased the rate to 5 bpm, which was the maximum rate the pump truck was capable of generating. At the maximum rate, the injection pressures fluctuated between 1,730 psi and 1,850 psi. The injectivity test ran for seven hours and injected approximately 1,000 barrels of brine. Based upon the results of the injectivity testing, D & L Energy Inc., proceeded with an application to convert the Northstar 1 well to Class II injection.

Due to the increased seismic activities near the Northstar 1 Class II injection well, in September 2011 the DOGRM required D & L Energy Inc., to perform tracer and spinner surveys to determine which geologic formations were receiving injection fluids and to ensure fluids were not going into the Precambrian basement rock.

On-site Activities Completed to Date

On Oct. 10, 2011, D & L Energy Inc., conducted the downhole tracer and spinner surveys at the Northstar 1 Class II injection well. All testing was witnessed by representatives from DOGRM. During the initial testing phase, it was determined that sediment fill-up had accumulated in the Northstar 1 from the original total depth of 9,184 ft (2,799 m) back to a depth of 8,940 ft (2,725 m). The tracer survey test demonstrated that injection fluids were entering multiple porous and permeable zones within the permitted Knox through Mt. Simon injection zones directly below the casing seat at 8,215 ft (2,504 m). Numerous porous rock zones from 8,222 ft to 8,928 ft (2,506–2,721 m) were documented receiving injection fluids. The spinner survey failed to properly work in the open-hole completion and did not provide any usable data.

After the October testing of the Northstar 1 Class II injection well, D & L Energy Inc., was required by the DOGRM to plug back the bottom of the wellbore with cement, since it penetrated approximately 200 feet into the Precambrian basement rocks. However, since the tracer survey demonstrated that the injection fluids were entering the permitted injection intervals, it was agreed to allow D & L Energy Inc., to get the Northstar 2 Class II injection well up and running prior to shutting down the Northstar 1 Class II injection well and conducting the plug-back cementing operations. Unfortunately, the 4.0-magnitude seismic event happened prior to conducting this plug-back cementing operation.

THE OHIO SEISMIC NETWORK AND HISTORIC EARTHQUAKES IN OHIO

More than 200 felt earthquakes have been noted in Ohio since 1776, including at least 15 events that have caused minor to moderate damage (fig. 20). The largest and most damaging earthquake occurred on March 9, 1937, in western Ohio and caused notable damage in the town of Anna (Shelby County), where nearly every chimney in town was toppled. The Anna school was so badly damaged that it was razed.

Seismic monitoring in Ohio was sporadic until establishment of the OhioSeis in 1999. Prior to the establishment of the OhioSeis in 1999, various smaller monitoring networks were in place sporadically throughout the state. However, until the establishment of OhioSeis, the Ohio Geological Survey was unable to accurately determine any seismic events below an approximate magnitude of 3.0 in Ohio consistently. Coordinated by the Ohio Geological Survey, OhioSeis initially was funded by the Ohio Emergency Management Agency (Hansen and Ruff, 2003). Volunteer-operated seismic stations were located at 15 colleges, universities, and other institutions. Additional institutions joined the network, which now consists of 26 stations throughout the state (fig. 21). The station at Youngstown State University (Station YSUO) joined the network in 2003 and is under the direction of Dr. Jeffrey Dick.

Youngstown Earthquakes

Prior to the March 2011 earthquakes, there has been no record of felt earthquake activity from epicenters located in Mahoning County, including the Youngstown area, in modern times. There have been earthquakes originating outside of Mahoning County that have been felt in the Youngstown area, including (1) a 5.2-magnitude event on Sept. 25, 1998, to the north-northeast in Mercer County, Pa.; and (2) the second-largest earthquake centered in Ohio, a 5.0-magnitude event, on Jan. 31, 1986, in southern Lake County. The nearest recorded event to Youngstown was a 3.0-magnitude earthquake recorded by OhioSeis on Aug. 7, 2000, in southern Portage County, just north of Alliance (fig. 20).

On March 17, 2011, two small earthquakes were recorded at Youngstown. The first event of 2.1-magnitude was a foreshock of a 2.6 magnitude event 11 minutes later. The latter event was felt by a number of Youngstown residents. Subsequently, 10 additional earthquakes above 2.0-magnitude were detected within the same general area (table 5; fig. 22).

Portable Stations

Four highly sensitive, portable seismic stations, on loan from Lamont-Doherty, were deployed in the epicentral area of the Youngstown earthquakes (fig. 22) on Dec. 1 by personnel from Lamont-Doherty, the Ohio Geological Survey, and Youngstown State University (YSU). YSU will maintain the stations and download data.

In early January, Lamont-Doherty installed a USGS NetQuakes sensor at OhioSeis Station YSUO. This sensor, which is connected to the Internet, triggers (begins recording) when an earthquake occurs and data is sent to the USGS. This sensor triggered on the small earthquake on Jan. 13, 2012, providing our first notification of this unfelt event.

Focal Depth

Focal depth refers to the depth below the surface at which an earthquake occurs. Accurate focal depths are difficult to calculate without several high-quality seismometers very close to the epicenters. For this reason, OhioSeis, the USGS, and the Geological Survey of Canada, among others, use a standard (fixed) focal depth of 3.1 mi (5 km) in the eastern United States in earthquake location software.

The portable seismometer array installed by Lamont-Doherty recorded the events on Dec. 24 and Dec. 31 (see Appendix 2) and provided the first accurate focal depths of 2.21 mi (3.55 km) and 2.29 mi (3.68 km), respectively.

Epicentral Accuracy

Epicentral coordinates (latitude/longitude of the epicenter) exhibit some variance between individual earthquakes. The epicenter is calculated by picking the arrival times of primary (P) and secondary (S) phases (waves) at each station. Variations can occur due to the size (magnitude) of an earthquake, clarity of the precise pulse of a phase arrival (to 0.1 seconds [s]), cultural noise at the station at the time of an earthquake, which stations are used in the location program, and other factors. Therefore, it should not be construed that the variations in epicentral locations for the Youngstown sequence are at a wide variety of locations, although there could be minor variations. The error ellipse indicates the statistical variance in the accuracy of the epicenter; that is, the earthquake could have been anywhere within the ellipse defined by the location program. The average latitude/longitude of epicentral coordinates for eight Youngstown-area events was: 41.11, -80.69.

A key factor in evaluating the accuracy of the earthquake epicenters in the Youngstown area is Station YSUO, which recorded each earthquake quite clearly with very sharp Pg and Sg arrivals and had GPS timelock throughout the sequence. For each event, the S-P time (S-wave arrival time minus the P-wave arrival time) is 0.8 s. These are direct ray paths (Pg and Sg phases) to Station YSUO and suggest that the foci of the earthquakes are at a precise and unvarying distance from the station. Comparison of the seismograms from each event, as recorded at Station YSUO, shows little variation except for amplitude, which is dependent on magnitude, suggesting that all events have a similar focal mechanism and originated from a similar source area.

Calculations of the epicenters for the Dec. 24 and Dec. 31 events, from the data obtained by the portable seismometers in the epicentral area, indicate that they were separated by about 328 ft (100 m).

Focal Mechanism

No faults have been mapped in the Youngstown area. Known regional faulting in this portion of northeastern Ohio and western Pennsylvania has a northwest–southeast trend.

The fault-plane solution (focal mechanism), calculated by Dr. Won-Young Kim at Lamont-Doherty, for the Dec. 31 event indicates that the sense of movement on the fault was strike-slip (horizontal). The analyzed seismic data show nodal planes striking 265° and 171° from north. Without additional data, either of these directions could be the fault-plane direction (see Appendix 2 – Fig. 2). The direction of 171° would generally align with a northwest trend, whereas the 265° direction generally would agree with a northeast trend. These calculations agree well with those done independently by Dr. Robert Herrmann at St. Louis University based on data from regional seismic stations.[7]
John Armbruster of Lamont-Doherty has been monitoring and analyzing microseismic events (less than 2-magnitude, most less than 1-magnitude) using the portable seismic monitors positioned around Youngstown. At time of this writing, he still is

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[7]See http://www.eas.slu.edu/eqc/eqc_mt/MECH.NA/20111231200501/index.html.
[8]Accessible at: http://earthquake.usgs.gov/earthquakes/dyfi/. A link to this site is on the OhioSeis home page: http://www.ohiodnr.com/ohioseis.

developing a report but indicates that he has determined preliminary hypocenters of 11 events; they define a zone about 1.4 mi (2.3 km) long striking N. 65° E., with the Northstar 1 well near the center. The hypocenters of the larger events are in the western end of the zone. The fault plane defined by the hypocenters dips at ~60° N. The bottom of the well is about 1,640 ft (500 m) above the fault plane. Thus the microseismic events now define the fault plane to be northeast–southwest–oriented (N. 65° E.). This is nearly perpendicular to the trend of the Mahoning River Valley lineament. Large fault systems will typically contain faults perpendicular to the main trend (synthetic and antithetic faults) so this new solution does not negate the Mahoning River trend from being suspect, but it does complicate the interpretation.

Felt Reports

People tend to be good "seismometers," particularly for small, shallow earthquakes, as those closest to the epicenter are likely to feel the earthquake most strongly. Some people who feel an earthquake submit a felt report to the USGS "Did You Feel It" website. These felt reports immediately are forwarded from the USGS server to the OhioSeis email. Therefore, OhioSeis receives both zip code and street addresses (if provided by the individual) for the felt reports along with other data.

The number of felt reports for a particular earthquake can vary considerably depending on the magnitude of the event, proximity to a population center, time of day (few people feel small ones in the middle of the night), and the awareness of people at a reporting site. The initial event in the sequence (not including the very small foreshock 11 minutes before the main shock) at 6:53 a.m. EST., on March 17, generated 27 felt reports. The largest event in the sequence, on Dec. 31, generated more than 4,000 felt reports and was felt throughout northeastern Ohio, parts of western Pennsylvania, and northward into Ontario, Canada.

Seismic Events in Relation to Injection Well

The latitude/longitude coordinates of the Northstar 1 well are: 41.120, -80.683. The Station YSUO coordinates are: 41.104, -80.648. The distance between the well and Station YSUO is 11,266 ft (2.12 mi [3.43 km]). Average epicentral coordinates for all events are: 41.11, -80.69. Distance between Northstar 1 well and average epicentral coordinates is 4,134 ft (0.78 mi [1.26 km]). Depth of Northstar 1 well is 9,192 ft (1.74 mi [2.77 km]). Dec. 24 and Dec. 31 focal depths equal 11,647 ft (2.21 mi [3.55 km]) and 12,074 ft (2.29 mi [3.68 km]), respectively. (See fig. 22 for the locations of all seismic events, permitted injection wells, and seismometers in the Youngstown study area.)

CONCLUSION

Induced Seismicity

It is very difficult for all conditions to be met to induce seismic events. This is evident in the very small number of documented injection-well-induced seismic events in the United States (less than 20) versus more than 144,000 injection wells in operation. A Class I injection well in Ashtabula County is thought by some to have induced a series of earthquakes in 1987 (Seeber and Armbruster, 1993), while some researchers question this conclusion (Gerrish and Nieto, 2005). Approximately 10 percent of these wells have had open-hole sections within the Precambrian and some have operated successfully for decades. It is very difficult to predict with certainty that a specific location will encounter or be close to a Precambrian fault.

To induce an earthquake (as opposed to microseismicity associated with shallow injection operations or hydraulic fracture stimulations), a number of circumstances must be met:

1. A fault must already exist within the crystalline basement rock;
2. That fault must already be in a near-failure state of stress;
3. An injection well must be drilled deep enough and near enough to the fault and have a path of communication to the fault; and
4. The injection well must inject a sufficient quantity of fluids at a high enough pressure and for an adequate period of time to cause failure, or movement, along that fault (or system of faults).

A number of coincidental circumstances appear to make a compelling argument for the recent Youngstown-area seismic events to have been induced:

1. The Northstar 1 well began injection operations in December 2010. Roughly three months later, the first seismic events were noted and were fairly close to the well;
2. Subsequent seismic events were clustered around the vicinity of the wellbore;
3. Evidence of open fractures and permeability zones within the Precambrian is interpreted in some of the geophysical logs obtained from within the Northstar 1 well (figs. 16 a, b, c and 17); and
4. Once sufficient monitoring equipment was in place, the focal depths of events were found to be about 4,000 ft (1,220 m) laterally and 2,500 ft (760 m) vertically from the wellbore terminus.

It appears there are observed permeability zones within the Precambrian basement rock in the "piggyback" logs recorded by the Battelle Memorial Institute during the drilling of Northstar 1.

These logs were not available to inform regulators of possible issues in geological formations prior to well operation. Instead, Battelle produced and made the logs available to provide geologists with additional information on the region's geological formations. In the future, ODNR will require the Class II well owner to provide a suite of geophysical logs germane to the respective injection well.

To establish a better understanding of what may have happened, further analysis and detailed modeling of all factors must be completed on the Northstar 1 well and the surrounding geology. Much of this work is already underway through ODNR and cooperating agencies and institutions.

RECOMMENDATIONS

The reforms listed below will make Ohio's Class II deep injection wells among the most carefully monitored and stringently regulated disposal wells in the nation. Ohio will seek the following reforms to its Class II deep injection well program:

- Requires a review of existing geologic data for known faulted areas within the state and avoid the locating of new Class II disposal wells within these areas;
- Requires of a complete suite of geophysical logs (including, at a minimum, gamma ray, compensated density-neutron, and resistivity logs) to be run on newly drilled Class II disposal wells. A copy of the completed log, with analytical interpretation will be submitted to ODNR;
- Evaluates the potential for conducting seismic surveys;
- Requires operators to plug back with cement, prior to injection, any well drilled in Precambrian basement rock for testing purposes.
- Requires the submission, at time of permit application, of any information available concerning the existence of known geological faults within a specified distance of the proposed well location, and submission of a plan for monitoring any seismic activity that may occur;
- Requires a measurement or calculation of original downhole reservoir pressure prior to initial injection;
- Requires conducting a step-rate injection test to establish formation parting pressure and injection rates;
- Requires the installation of a continuous pressure monitoring system, with results being electronically available to ODNR for review;
- Requires the installation of an automatic shut-off system set to operate if the fluid injection pressure exceeds a maximum pressure to be set by ODNR;
- Requires the installation of an electronic data recording system for purposes of tracking all fluids brought by a brine transporter for injection;

ODNR is considering these changes to deep Cambrian-Precambrian Class II injection wells either through specialized attached permit conditions or through potential changes to either Section 1509 of the Ohio Revised Code or Section 1501:9-03-01 through 1501:9-03-10 of the Ohio Administrative Code. These recommended changes are being proposed to ensure protection of the health and safety of the citizens of Ohio.

In addition, ODNR is in the process of identifying an "outside" expert with experience in seismicity, induced seismicity and Class II injection wells to conduct an independent review of the currently available technical information, as well as information to be supplied by the injection well owners in the vicinity of the Northstar 1 well. This independent analysis will provide a scientific third party evaluation and analysis of all technical information to ensure thoroughness of the process.

List of Figures & Captions, Tables and Appendices

FIGURE 1.—General site map showing detail of the Youngstown, Ohio, area and locations of the Northstar #1 injection well and the Ohio Seismic Network YSUO station. Basemap from the USGS Youngstown 7½-minute topographic quadrangle map.

and others (1993).

Appendix 19. Public notice for the application to drill the Northstar Khalil 3 well.

Appendix 20. Permit as issued to drill the Northstar Khalil 3 well.

Appendix 21. Request for change of owner.

Appendix 22. Application to drill the Northstar Collins 6.

Appendix 23. Public notice for the application to drill the Northstar Collins 6 well.

Appendix 24. Permit as issued to drill the Northstar Collins 6 well.

Appendix 25. Well completion record for the Northstar Collins 6 well.

Appendix 26. Application to drill the Northstar Nexlev 5 well.

Appendix 27. Public notice for the application to drill the Northstar Nexlev 5 well.

Appendix 28. Objections to the application to drill the Northstar Nexlev 5 well filed by Hubbard Township Trustees.

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