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Ohio Geology

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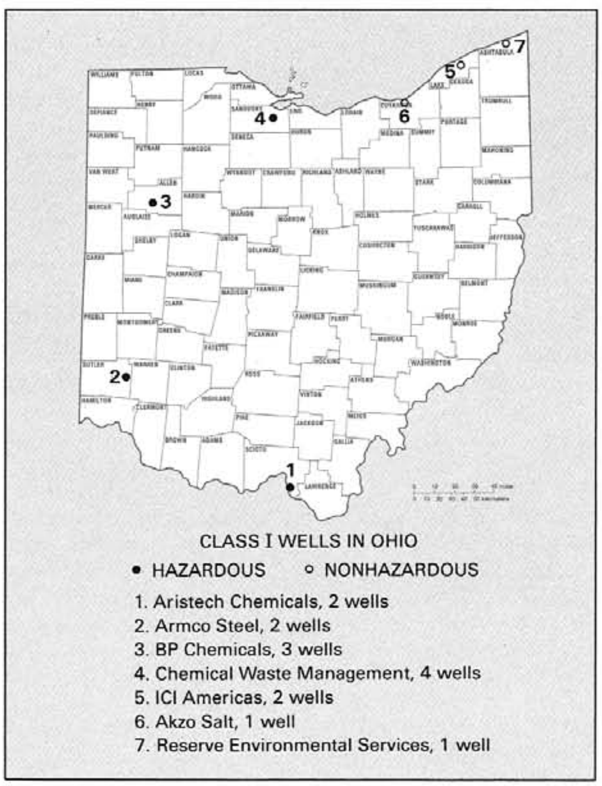
INDUSTRIAL-WASTE-DISPOSAL WELLS IN OHIO

by Lawrence H. Wickstrom

Depending upon your age, you may remember the common, pre-1970's image of industrial waste being openly dumped in American waterways. In Ohio such practices led to the near ruination of Lake Erie, the burning Cuyahoga River, and a proliferation of "No Swimming" signs. Fortunately, discharge of wastes into our surface waters is strictly regulated today and many of our lakes and streams are well on their way to recovery; but this fact doesn't mean those wastes are no longer generated. The disposal of a significant volume of today's liquid industrial-waste products is by deep, subsurface injection wells. Nationwide, more than 8 billion gallons of industrial wastes are annually disposed of by deep injection wells. Such huge volumes of liquid waste, permanently stored beneath our feet, have more and more citizens asking "Where is it all going?"

Ohio currently has 15 industrial-waste-disposal wells in operation at seven facilities. Four additional wells have been plugged, and two new wells have been drilled but are not currently permitted to operate. Approximately 575 million gallons of waste are injected annually into the deep subsurface strata of our state through the 15 permitted wells.



Map of Ohio showing location of Class I injection wells.

The wastes originate from a variety of industrial processes including steel processing, fertilizer and fungicide production, and plastics production. Some of the newer components of this waste stream are products of other waste-disposal and clean-up methods such as incinerator scrubber water, liquids recovered from remediation of industrial spills, and leachate from solid-waste disposal sites.

A quick look at the list of waste generators illustrates how hard it would be for our society to do without the products from these industries. How different our lives would be without steel and metal alloys or the multitude of plastic products! And without modern fertilizers and fungicides, which dramatically increase the yield of our farmlands, the balance of American society as well as international relations would be altered. Add to this list the thousands of jobs and the millions of dollars annually pumped into our economy by these industries and one can quickly see that we are dependent upon these industries and thus must deal with the wastes generated. Furthermore, we must always remember that how we deal with these wastes now will affect the well-being of generations to come.

BACKGROUND

The U.S. Environmental Protection Agency's (USEPA) Underground Injection Control (UIC) program recognizes five classes of injection wells. These classes are defined, in part, by the well's relationship to an Underground Source of Drinking Water (USDW). The Safe Drinking Water Act (SDWA) of 1974 designated as a USDW any aquifer whose water contains a concentration of less than 10,000 mg/l of total dissolved solids. The five injection-well classes are:

Class I wells—used for injection of industrial or municipal waste fluids beneath the lowermost formation containing a USDW.

Class II wells—used for injection of brines produced by oil and gas production or fluids used for enhanced recovery of oil or natural gas.

Class III wells—used for injection of fluids for the extraction of soluble minerals, such as salt-solution mining in northeastern Ohio.

Class IV wells—used for injection of hazardous or radioactive wastes into or above a USDW. As of May 11, 1984, all Class IV wells have been banned in the U.S.

Class V wells—wells not covered by Classes I through IV. These wells are generally used for the disposal of nonhazardous fluids and include storm-water drainage wells, industrial drainage wells, heat-pump and air-conditioning return wells, cesspools, septic systems, floor drains, and sumps.

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OHIO Department of Natural Resources

George V. Voinovich, Governor • Mike DeWine, Lt. Governor • Frances S. Buchholzer, Director

FROM THE STATE GEOLOGIST . . . by Thomas M. Berg

OHIO'S BASEMENT—REVISITING THE PRINCESS ON THE PEA

If someone were to ask me what was in my basement, I think I'd be a little embarrassed. I would have to admit that it's more or less organized chaos. I still have boxes that have not been unpacked since my move to Ohio almost four years ago. I have rock samples and geological journals that I don't want to part with because, as I tell my wife, ". . . I've got plans for that stuff!" I did get most of my tools and workbench in order last summer, but chaos is slowly creeping back into that area, too. Of course, our beloved cat lives very happily for most of the time in the midst of all the basement disarray, and adds her contribution of furballs.

I imagine digging through anyone's basement can be very revealing. Things saved, items never unwrapped, secrets hidden in the bottoms of trunks, can tell much about the past and its influence on the present. Basements can be scary places too—dark and damp, with unknown horrors lurking in the shadows. I'll never forget the day when as a curious six-year-old I discovered a cache of various animal skulls in the basement of a rented house. I wouldn't go near the basement door for months!

In the Earth's crust beneath Ohio there is a domain called the "basement" about which we know very little. Geologists have used the term basement for many years to refer to the very old crystalline rock formations beneath the Paleozoic sedimentary rock layers that we see spread out in relatively neat and flat order across the state. Until about a decade or so ago, most geologists in Ohio and surrounding states spent little time worrying about the basement rocks. The general notion we used to carry around in our heads was that the basement was a vague mix of Precambrian (more than 570 million years old) igneous and metamorphic rocks that had been shaved down to a relatively flat surface before the Paleozoic formations were deposited. What we have learned in the 80's and early 90's points to something far, far more complex than we ever imagined!

First of all, we now know that Ohio bears the deep scar—a continental suture—of a collision (the Grenville orogeny) of two primordial continents. This 30-mile-wide scar running nearly north-south through the western half of Ohio's basement—called the Grenville Front—marks the zone where a billion-year-old tectonic plate composed of metamorphic rocks smashed against the even older (1.4 billion years old) igneous rocks of the continental interior. This dramatic boundary between two very different parts of the Earth's crust was suspected almost 35 years ago when some radiometric dating was done on samples of Ohio basement. The view was further refined by U.S. Geological Survey geophysical mapping released in 1984, and by deep seismic profiling of Ohio completed in late 1987 (see *Ohio Geology*, Fall 1987 and Winter 1989).

The most startling discovery about Ohio's basement is that it was torn apart even before the Grenvillian continental collision. Evidence brought to light by the Ohio Survey's deep core in Warren County indicates the presence of thick accumulations of sandstone buried in a huge rift basin in the basement beneath western Ohio (see *Ohio Geology*, Summer 1989). Work recently completed by a consortium of the Ohio, Indiana, and Kentucky Geological Surveys and supported by private industry has revealed that over 20,000 feet of Precambrian sedimentary rocks fills parts of the fault-bounded rift complex called the "East Continent Rift Basin." That's about five times the entire thickness of the overlying Paleozoic succession! This rifting of the continent took place about 1,200 million years ago, long before there was any form of life on land, and mostly single-celled organisms lived in the sea.

The recent investigation of the East Continent Rift Basin has also revealed that the basement rocks were wrenched by near-vertical faults, some of which were active during the Early to Middle Paleozoic—Precambrian faults reactivated by later continental movements.

It's going to take a while for geologists to figure out Ohio's basement, and it will be a difficult task because the basement is completely covered by younger Paleozoic strata. Readers of *Ohio Geology* may not care about the chaos in my own basement, but they should care very much about the geologic framework of Ohio's basement. Remember Hans Christian Andersen's fairy tale of the "Princess on the Pea"? The prince wanted a real princess, but in every princess he met there was something that was not quite right. One stormy night, the king found a girl who said she was a princess but she didn't look like one because she was bedraggled and rain soaked. The old queen devised a fool-proof test. She secretly placed a pea at the bottom of the bed where the princess was to sleep and covered it with 20 mattresses and 20 comforters. When the young lady got up in the morning, she told the king and queen that she had hardly slept all night and woke up with bruises. The king and queen had found a princess for the prince! No one but a real princess could be so delicate as to feel a pea through 20 mattresses and 20 comforters.

Ohio's Paleozoic strata are like the 20 mattresses and 20 comforters. At first glance, we don't recognize much reflection of the complex basement rocks in the overlying layers of flat sedimentary rocks. But the "peas" are there, and we do feel them. Precambrian faults have been reactivated, disrupting the lateral continuity of younger Paleozoic formations. Economically important coal seams are missing along zones of reactivated Precambrian structures. The distribution of oil and gas in the deep Knox Dolomite of eastern Ohio is partly related to reactivated basement fracture zones. The arrangement of buried-valley aquifers in northwest Ohio appears to be related to Precambrian wrench faults. The lateral continuity of the Mt. Simon Sandstone is partly controlled by the paleotopography of the Precambrian surface, replete with gabbroic hills and ancient volcanic intrusions. The Anna seismic area rests astride a tightly faulted part of the Precambrian rift complex.

As we move toward the next millennium, your Division of Geological Survey needs to do the drilling, geophysical surveying, remote sensing, and subsurface investigations to thoroughly characterize the basement rocks of our state. This effort will take time, talent, and adequate funding, as do the other necessary geologic mapping and geologic framework investigations required of the Survey. But we cannot put off the investment. The practical results of basement investigations impact how we deal with mineral resources, ground water, waste disposal, fossil fuels, geothermal energy, and seismic hazards.

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MINERAL INDUSTRIES REPORT AVAILABLE

The *1991 Report on Ohio mineral industries*, compiled by Survey geologist and mineral statistician Sherry L. Weisgarber, provides production, sales, and employment statistics for the coal, limestone/dolomite, sand/gravel, sandstone/conglomerate, clay, shale, gypsum, salt, and peat industries, plus production and value statistics for oil and gas. The report includes alphabetical and by-county directories of coal and industrial-mineral mine operators and a map of the locations of reporting producing coal mines and all industrial-mineral mines in 1991. The feature article in the 1991 report is "Industrial minerals in Ohio—production trends and multi-production operations," co-authored by David A. Stith, Survey Geologist and Head of the Mineral Resources and Geochemistry Section, and Sherry L. Weisgarber.

Copies of the *1991 Report on Ohio mineral industries*, including the map, are available from the Survey for $7.29, including tax and mailing. The map is available separately for $3.06, including tax and mailing.

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Under this system of classification, Ohio's deep industrial-waste-disposal wells are all in the Class I category. The USEPA further subdivides this category on the basis of whether the injectate is classified as hazardous or nonhazardous waste. Three of Ohio's Class I facilities inject hazardous waste, and four inject nonhazardous fluids.

Deep injection of industrial wastes has been practiced since the 1950's. However, no federal regulations governed these wells until passage of the 1974 SDWA. Prior to 1974, the individual states regulated the drilling and operation of Class I wells. In Ohio, the Department of Natural Resources (ODNR), Division of Oil and Gas originally had the responsibility of overseeing this program.

In 1980 the USEPA promulgated most of the current UIC regulations. Under these rules a state may develop a UIC program and apply for primary responsibility ("primacy") for that program. A state must use the federal regulations as a baseline and may develop more stringent regulations. After passage of the federal regulations, the Ohio Environmental Protection Agency (Ohio EPA) began taking a more pronounced role in the Class I program and in 1985 received primacy from the USEPA. Under current Ohio law, the Ohio EPA is required to have review and technical assistance on all Class I permit applications from the ODNR Divisions of Geological Survey, Oil and Gas, and Water, and, if the proposed well is in a coal-bearing area, the Ohio Department of Industrial Relations, Division of Mines. The review by these divisions provides the Director of the Ohio EPA with information that relates the Class I well-permit decision to protection of mineral and oil and gas resources, as well as ground-water availability. Comments generated by ODNR and the Department of Industrial Relations are considered by the Director of Ohio EPA in establishing permit conditions, if it is decided that a permit to drill or a permit to operate should be issued.

Under Ohio law, all Class I well permits are issued for not less than four years nor more than six years. The operator must update the permit application and submit it for review prior to the expiration date. The permits for the seven Class I facilities in Ohio are staggered so they do not all come up for review at the same time. Review of permit renewals, as well as permit modification requests, new well requests, appeals, or other Class I well issues requires the Survey's Subsurface Stratigraphy and Petroleum Geology Section to spend a considerable amount of time on the geology of Class I sites.

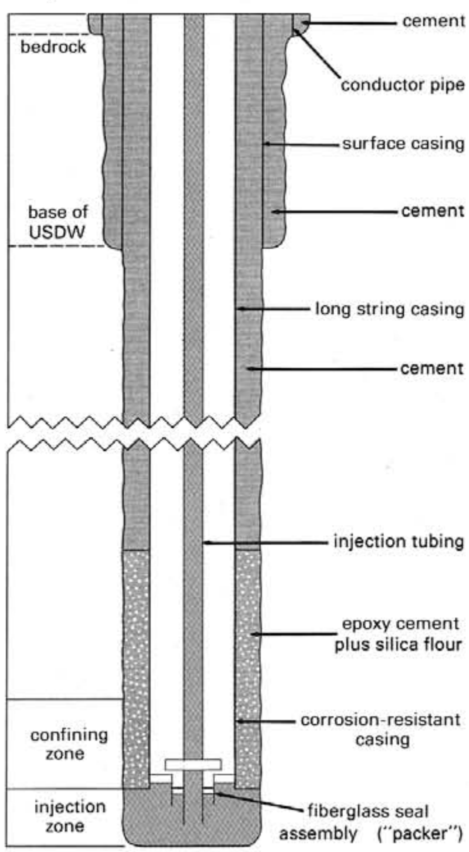
In 1984 the U.S. Congress passed the Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act. Under this legislation, which has had a large impact on the regulation of some Class I wells, land disposal of all untreated hazardous waste is prohibited after specified dates unless the USEPA has determined that such disposal practices are protective of human health and the environment. These regulations are commonly known as the "Landban Program." Class I well operators have had to submit lengthy documents demonstrating that their sites and practices are safe and that human safety and welfare are protected. Under Landban, the petitioner must demonstrate that, to a reasonable degree of certainty, there will be no migration of hazardous constituents from the injection zone as long as the waste remains hazardous.

Beginning in 1987, the USEPA through the Ohio EPA contracted with the Division of Geological Survey to assist in the review of the Landban petitions for the four hazardous-waste-injection sites in Ohio (one of these sites has subsequently applied for and received nonhazardous status). This lengthy and detailed process is just now coming to an end. The federal regulations have strengthened the Ohio program and have allowed a detailed analysis of the geology, construction, and operation of these injection wells.

WELL CONSTRUCTION

The main design goal for all Class I wells is to deliver the waste to the permitted injection zone and keep it isolated without contaminating any USDW. Most problems with deep-well injection in the United States are attributable to poor well design, construction, and/or operation standards or requirements.

The general construction of a typical Class I injection well is illustrated in the accompanying diagram. The casing seals off formations above the injection zone and provides pressure control for the well operation. In some areas covered by thick unconsolidated deposits, a large-diameter conductor pipe is driven through these deposits into bedrock. A large-diameter hole is then drilled below the base of the deepest USDW. Steel surface casing (approximately 2 inches narrower than the hole diameter) is run to the bottom of the hole, centered, and cemented in place. The cement job is tested for bonding throughout its length.



Schematic diagram showing typical Class I well construction.

The borehole is then extended to a predetermined total depth, and open-hole geophysical logs are run. These logs are useful in determining the properties of the rocks encountered in the well. The "long string" casing is lowered through the surface casing to the prescribed depth in the hole, centered, cemented from the bottom to the surface, and tested. Depending on the material to be injected, special cements may be required. Typically, the lower portion of the long string casing is constructed of fiberglass, fibercast, or corrosion-resistant steel.

The injection tubing is placed inside the long string and sealed from the casing above by a packer at the top of the injection zone. The space between the injection tubing and the inner wall of the long string casing is called the annulus. The annulus is filled with an inert fluid (such as water and sodium chloride) and pressurized. The operator is required to constantly monitor the annulus pressure and report it to the Ohio EPA. Leakage from the tubing to the casing or from the casing to the surrounding rocks will cause either a pressure increase or decrease. The actual injection pressure is also constantly monitored. A fluctuation in either of these monitored pressures will automatically set off alarms and trigger shutdown devices to stop the injection pumps. The well operators are required to file monthly reports of their injection activities listing monitored pressures, injectate volumes, and injection rates.

A maximum allowable injection pressure is set for each well. This limit must be below the fracture pressure for the well. This limit insures that the operation of the injection well will not artificially initiate and propagate fractures in the injection-zone rock or the confining strata that protect the USDW's. Wells at three Class I sites in Ohio have had fracture treatment as part of their well-completion programs. Although well stimulation is not prohibited by state or federal law, the Division of Geological Survey believes that artificial fracturing in Class I injection wells is undesirable for several reasons. Most studies indicate that induced fractures at depth will be vertical. Once fractures are initiated they may be propagated further by operating the well at pressures close to the fracture limit. The integrity of injection sites is heavily dependent on modeling the flow of injectate away from the well bore and predicting the buildup of pressure as a result of continued injection. If the injectate is flowing along fractures it is not possible to reliably model the waste front or pressure front generated.

Proper well-treatment design and implementation are crucial to ensure that the rock units that make up the injection zone and confining strata will not be fractured in a way that will allow waste migration outside of permitted intervals. The Ohio EPA reviews plans for any well treatment to ensure that the integrity of the rock units will not be violated by the proposed treatment process.

GEOLOGIC CONSIDERATIONS IN CLASS I INJECTION

Many geologic factors must be considered in choosing a suitable subsurface location for liquid-waste injection. Some of the major factors are: (1) the capacity of the geologic units to accept and confine the waste, (2) structural geologic setting, and (3) presence or absence of valuable economic mineral resources within the potential area of influence.

Injection reservoir capacity

The three main parameters affecting the storage capacity of a geologic unit are its porosity (percentage of pore space), permeability (degree of connection of pore spaces), and thickness. Another factor which must be considered is the lateral extent and consistency of a geologic unit. A thick, continuous geologic unit with high porosity (storativity) through which liquids may pass easily (transmissivity) is most desirable.

The Division of Geological Survey has determined that the Cambrian-age Mt. Simon Sandstone is, throughout most of the state, the most suitable unit for emplacement of waste through Class I wells. Statewide, the Mt. Simon is the lowest Paleozoic sedimentary reservoir rock known; depth to the Mt. Simon ranges from 2,500 to over 10,000 feet below the surface. In western and central Ohio the Mt. Simon is a fine- to coarse-grained, feldspathic to arkosic quartzose sandstone containing minor amounts of interbedded dolomite and shale. Its porosity averages about 13 percent and overall permeability is about 40 millidarcys, which are very high compared to most of Ohio's reservoir rocks. For comparison, a "good" producing "Clinton" sandstone well (the "Clinton" is Ohio's leading oil and gas producing unit) averages approximately 8 percent porosity and 5 millidarcys permeability.

In eastern Ohio, the Mt. Simon is a dolomitic sandstone and is less suited for use as an injection unit: porosity is about 8 percent and permeability is about 10 millidarcys. The boundaries or characteristics of this west-to-east facies change in the Mt. Simon have not been mapped in detail.

In general, the thickness of the Mt. Simon Sandstone is fairly consistent throughout any particular area considered for injection purposes. Statewide, the thickness of the Mt. Simon ranges from about 44 feet to more than 300 feet, although there are areas where the Mt. Simon is absent because of depositional or structural irregularities.

Thickness map of the Cambrian Mt. Simon Sandstone (from Janssens, 1973).

Characteristics of the confining strata

In order to keep the waste from moving vertically toward a USDW or potentially valuable mineral resources, the reservoir rock for the waste should be underlain and overlain by strata with opposite flow characteristics, that is, a thick, continuous rock unit with very low porosity and permeability which will impede the flow of the injectate. Such rock units are called aquitards.

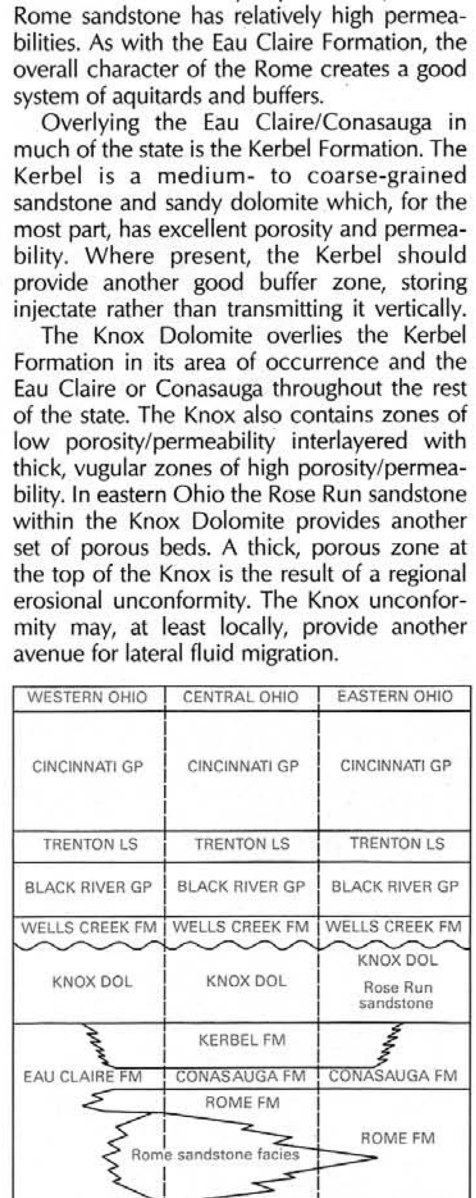
The Mt. Simon Sandstone is underlain by Precambrian crystalline rocks (billion-year-old granites, gneisses, gabbros, and metasedimentary rocks) of the Grenville Province in central and eastern Ohio and by Precambrian Middle Run Formation sandstones in much of western Ohio. The Grenville-Province rocks are all mostly impermeable. The Ohio Survey's deep stratigraphic test well in Warren County, Ohio, "discovered" the Middle Run Formation (see *Ohio Geology,* Summer 1989). Ongoing investigations of selected samples from other wells in western Ohio have extended the limits of this pre-Mt. Simon sedimentary unit to a far broader area than originally anticipated. Initial analyses of cores from two wells (Warren and Allen Counties) show that this unit has very low porosity and permeability but a high degree of fracturing. Both the Middle Run and the Grenville rocks should provide adequate seals to downward migration of wastes, although additional research is needed on Precambrian lithologies, contacts, and structures.

Overlying the Mt. Simon Sandstone in western Ohio are rocks of the Cambrian Eau Claire Formation. The Eau Claire is composed of interbedded shales, siltstones, fine-grained sandstones, and argillaceous dolomites. Overall, this unit normally has porosity of less than 4 percent and permeability of less than 1 millidarcy. However, some individual shale, siltstone, and dolomite layers within the unit act as very effective aquitards, having porosities of less than 1 percent and permeabilities of less than 0.1 millidarcy. Interbedded with these layers are siltstone and sandstone units of higher porosities and permeabilities. As a whole, the Eau Claire provides a very good confining layer for wastes disposed of in Class I wells; any fluids which might migrate through the less permeable units are "absorbed" by the higher permeability units.

In west-central Ohio the Eau Claire changes laterally eastward to the Rome Formation and the overlying Conasauga Formation. The Conasauga is very similar to the Eau Claire. In central Ohio the Rome is composed of a lower and upper dolomite separated by a sandstone. Farther east the sandstone disappears and the Rome is composed almost wholly of dolomite. The Rome dolomite is fairly impermeable, but the Rome sandstone has relatively high permeabilities. As with the Eau Claire Formation, the overall character of the Rome creates a good system of aquitards and buffers.

Overlying the Eau Claire/Conasauga in much of the state is the Kerbel Formation. The Kerbel is a medium- to coarse-grained sandstone and sandy dolomite which, for the most part, has excellent porosity and permeability. Where present, the Kerbel should provide another good buffer zone, storing injectate rather than transmitting it vertically.

The Knox Dolomite overlies the Kerbel Formation in its area of occurrence and the Eau Claire or Conasauga throughout the rest of the state. The Knox also contains zones of low porosity/permeability interlayered with thick, vugular zones of high porosity/permeability. In eastern Ohio the Rose Run sandstone within the Knox Dolomite provides another set of porous beds. A thick, porous zone at the top of the Knox is the result of a regional erosional unconformity. The Knox unconformity may, at least locally, provide another avenue for lateral fluid migration.



Diagrammatic stratigraphic chart of Precambrian through lower Ordovician strata in Ohio (modified from Janssens, 1973).

Above the Knox unconformity, in ascending order, are the Wells Creek Formation, the Black River Group, the Trenton Limestone, and the Cincinnati group. Although the Trenton and the Black River may contain locally porous zones, these Ordovician strata may be viewed as a thick (>1,500 feet) low porosity/permeability succession which will impede the vertical flow of effluent upward toward any USDW. Some limestones in the upper portion of the Cincinnati group are, in some areas of southwestern Ohio, the stratigraphically lowest USDW in the state. Above the Cincinnati group lie the Silurian carbonates, which are the primary aquifers for much of western Ohio. Therefore, the Ordovician carbonates and shales may be viewed as the last inhibitor of upward migration of wastes into any sources of fresh water in western Ohio.

As can be seen in the accompanying table, the total thickness of confining strata, from the top of the active injection interval to the base of the lowest USDW, at Class I facilities in Ohio (excluding Akzo Salt, Inc.) ranges from a minimum of 1,900 feet to 5,130 feet. Using the Mt. Simon as the primary receptor of Class I wastes insures the maximum protective thickness of strata below the lowest USDW.

Structural setting

In terms of structural geology, three areas of concern stand out when investigating the suitability of a Class I injection site: (1) the elevation of the injection interval relative to the surrounding structural setting, (2) the presence or absence of faults and/or fracture systems, and (3) the potential for induced seismic events.

In the subsurface environment, the natural flow of fluids, in general, follows the most direct path from areas of higher pressures to areas of lower pressures. Because the amount of overlying rock is the primary pressure-loading factor, this concept translates into flow from deeper environments to shallower environments along the path of least resistance. These normal flow rates are low—on the order of several inches per year at the depth of the Mt. Simon.

The injection rate and pressure will yield an approximate radial flow of the injectate laterally away from the well into the injection formation. Continued injection creates an area around the well where pressures are higher within the injection formation. The longer injection continues the larger the radius of this pressure front becomes. Thus, the fluid seeks to escape this higher pressure area in a radial pattern. Once away from the area of pressure influence caused by injection, the fluid resumes its natural flow pattern. This flow pattern is dependent upon the relationship of the site to the local structural setting.

If the site is located at the lowest portion of a downwarp or synclinal depression, the flow should continue to approximate a radial flow pattern, seeking lower pressure areas on the surrounding highs. If it is on the flank of a rise, the natural flow should be asymmetric toward the higher elevation. If the site is located at the top of an arch or anticlinal feature, lateral flow away from the injection site would be impeded by the natural flow (toward the injection well) of native formation fluids. This latter situation is undesirable because the injectate will then be inclined to migrate vertically should vertical routes exist.

Flow away from the injection site should follow the general principles given above unless:

- the integrity of the well construction fails;
- a permeability barrier is encountered, such as a nontransmissive fault or fracture, a sedimentary facies change, or the thinning of the injection unit against a lower permeability unit;
- a higher permeability avenue is encountered, such as a transmissive fault or fracture, artificial fractures induced in the rock, intersection with an unplugged well bore, or a facies change in the reservoir rock that results in a higher flow rate.

Aside from failure of a well's construction and the possibility of encountering an unplugged well bore, the potential for upward migration along a naturally occurring fault plane is probably the most serious threat to loss of integrity of waste confinement at a Class I site. Although fluid movement along a fault plane that is transmissive will probably proceed faster than through the confining strata, it may still proceed very slowly, from a human perspective. Injectate moving along a naturally occurring fault may take tens, hundreds, or thousands of years to reach a USDW, but it could still have undesirable effects when it does arrive. Because of this potential threat the Division of Geological Survey investigates every site as thoroughly as possible for any indication of the presence of faults.

That earthquakes can be induced by injection of fluids is a well-known phenomenon. Probably the most widely publicized and documented instance was the series of earthquakes triggered by military waste injection at the Rocky Mountain Arsenal near Denver, Colorado. Several recent earthquakes in northeastern Ohio have caused public concern that they too may have been triggered by deep injection wells.

When discussing the possibility of induced seismic events it is important to understand that injection activities do not *cause* earthquakes; rather, injection may *trigger* earthquakes. Earthquakes are caused by the accumulation of crustal elastic-strain energy in a rock body that raises the stress level of the body to critical levels near rupture. An earthquake occurs due to the sudden release of energy as stress is released, generally along pre-existing faults. Therefore, injection of fluids into the subsurface cannot, by itself, establish the conditions necessary to cause an earthquake. But the injection of fluids into the subsurface can increase the pore pressure along a pre-existing fault, which is already at or near a critical level of stress, to trigger a local release of seismic energy.

To reduce the risk that an injection well may trigger a seismic event, the U.S. Geological Survey has recommended that a review of the site should include: (1) a survey of recent and historic seismicity in the area, (2) measurement of stress in the reservoir rock, (3) assessment of the presence or absence of faults, and (4) determination that the intended injection zone has adequate porosity and permeability to store and transmit the waste at pressures well below the failure pressure of the rock. If the area appears to have any risk of seismic activity, a seismic monitoring program should be established.

To insure the integrity of the waste reservoir and to protect our mineral resources, the environment, and human well-being, the Division of Geological Survey began requesting seismic-reflection profiling and seismic-activity monitoring on Class I sites in the mid-1980's. Recently passed Ohio legislation includes authorization for the Director of the Ohio EPA to require such data collection on all Class I sites. Seismic profiling is the least expensive and best available technology to reveal geologic structures and details of stratigraphy over the area of potential influence. The use of seismic profiling is not foolproof; at best its resolution is normally about 30 feet (in terms of vertical offset) at the depths under consideration. However, it is much better than having data from only one or a few wells to evaluate an area of pressure

SUMMARY OF CLASS I WELL SITES IN OHIO

Company	Waste injected	Allowable surface injection pressure	Depth to Mt. Simon (feet)	Total confining interval (feet)	Injectate			Cumulative volume injected (gals)	Date of 1st well	No. of wells
					pH	Temp.	Sp. Gr.			
Akzo Salt	brine which leaks into mine	150 psi	1294* *Oriskany	1000	6.2	50	1.2	23,343,728	1971	1
Aristech	phenols, acetone, ammonia, etc.	1650 psi	5550	5000	10.4	75-105	1.02	1,273,765,591	1968	2
Armco Steel	spent HCl pickle acid including Fe, Cr, Pb	634 psi	2975	2500	1.0	88-150	1.21	166,382,777	1969	2
BP Chemicals	hydrogen cyanide, misc. organics, acrylonitrile, acetonitrile, salts, etc.	825 psi	2800	2350	5.0	70-110	1.025	4,204,701,489	1968	3
Chemical Waste Management	various; leachates, spent pickle liquors, incinerator scrubber H_2O	790 psi	2800	1900	<1.0	60-80	1.15	800,000,000	1976	4
Empire Reeves Steel Div.	spent H_2SO_4 pickle liquor; site closed Jan. 1971	1500 psi	4990	4490	<2.0		1.195	10,314,933 as of 10/70	1967	1
ICI Americas	agricultural fungicides and fertilizer waste products—Fe, Ca, Mg, chloroform, NaCl, etc.	1689 psi	6023 5643* *Conasauga	5130	9.9	56	1.025	389,248,481	1971	2
Reserve Environmental Services	spent acids from steel treatment and alloying industry	1450 psi	5880 5469* *Conasauga	4899	9.3	50-90	1.09	74,163,047	1985	1

Approximate total volume: 6,941,920,046 gals
Cumulative volumes as of early 1992

buildup which may reach 50 square miles or more. These data are proving to be a valuable tool in Class I site evaluations.

Mineral resources

With time and the continued growth of our industrialized society, more and more natural resources are thought of not just as routine commodities, but as essential commodities. When oil was first found in salt wells in 1812 it was viewed as a nuisance; now our culture is heavily dependent upon its availability and price. Furthermore, mineral resources are not renewable; some may eventually become so scarce that worldwide shortages and socioeconomic disruptions could result. A conservative approach seems wise when protecting mineral resources from contamination by wastes. To protect mineral resources, the Division of Geological Survey believes that the Mt. Simon Sandstone is the most appropriate formation for Class I waste injection.

FURTHER READING

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TRILOBITES FEATURED IN SURVEY'S GSA DISPLAY

Two large specimens of *Isotelus maximus*, the official state fossil of Ohio, were featured in the Survey's exhibit at the national Geological Society of America meeting in Cincinnati in October. These specimens are unique because they show evidence of having been bitten by a predator, most likely a large cephalopod, and apparently surviving the attack, because the exoskeleton exhibits signs of healing and repair.

Both specimens were collected from Upper Ordovician rocks by Dan Cooper of Fairfield, Ohio; the prone specimen (see photo) is from Highland County and the enrolled specimen is from eastern Indiana. Dr. Loren Babcock of the Department of Geological Sciences at The Ohio State University is studying the specimens. He notes that the large, prone specimen has a very severe wound on the right side of the head shield (cephalon) which would have disrupted a portion of the circulatory system. Callusing and regeneration of a portion of the exoskeleton in the vicinity of the wound and the development of a small, anomalous spine suggest that this trilobite survived its injuries—at least for a time. The smaller, enrolled specimen exhibits a large wound on the tail shield (pygidium).

Specimen of Isotelus maximus *exhibiting predator-inflicted injury to the right portion of the cephalon. Ordovician, Highland County, Ohio. Collected by Dan Cooper.*

A fund has been established to enable Orton Geological Museum at Ohio State to acquire these specimens for permanent exhibit. Donations can be sent to Dr. Stig Bergström, Curator, Orton Geological Museum, Orton Hall, The Ohio State University, Columbus, OH 43210.

NEW PUBLICATION ON EAST CONTINENT RIFT ZONE

As part of a unique cooperative effort, the Ohio, Indiana, and Kentucky Geological Surveys have jointly published a report on Precambrian rift zones in the tri-state area. This research was initiated by the completion of the Ohio Geological Survey's deep core hole in Warren County, Ohio, in 1989 in which a thick sequence of sedimentary rocks was discovered below the Cambrian Mt. Simon Sandstone. This Precambrian unit, which may be more than 20,000 feet thick in some areas, was subsequently named the Middle Run Formation and is of Middle to Late Proterozoic age.

The Middle Run Formation has been interpreted to represent the infilling of a widespread rift basin and is thought to be present in an extensive area of western Ohio, as well as in neighboring Indiana and Kentucky. A research group consisting of the geological surveys of the three states, with funding from private industry, investigated the extent and characteristics of the rifting in the tri-state area. The research group is known as the Cincinnati Arch Consortium (CAC).

The first in a series of projected publications was published as Ohio Geological Survey Information Circular 57, *The East Continent Rift Basin: a new discovery*. The Indiana and Kentucky Geological Surveys have published the same report under their own series designations. The report was authored by James A. Drahovzal, David C. Harris, and Dan Walker of the Kentucky Geological Survey; Brian D. Keith and Lloyd C. Furer of the Indiana Geological Survey; and Lawrence H. Wickstrom and Mark T. Baranoski of the Ohio Geological Survey.

The East Continent Rift Basin appears to be linked to Keweenawan rifting that formed the Midcontinent Rift System, an arcuate feature that stretches northward from Iowa, through the Lake Superior region, and southward across Michigan. The rifting appears to predate the Grenville orogeny, which thrust rocks over portions of the East Continent Rift Basin. Although hydrocarbons or economic mineralization has not as yet been found in the rift basin, structures associated with the basin may have influenced overlying Paleozoic rocks, which may contain such deposits.

This 25-page publication contains 10 maps and diagrams and a table listing oil and gas wells penetrating the Middle Run Formation in the tri-state area. IC 57 is available from the Division of Geological Survey for $6.23, which includes tax and mailing.

SURVEY PARTICIPATES IN 1992 NATIONAL GSA MEETING

The 1992 national meeting of the Geological Society of America, held in Cincinnati, Ohio, on October 26-29, featured considerable participation by staff of the Ohio Geological Survey. Perhaps the greatest commitment by the Survey involved the 18 field trips associated with the meeting. State Geologist Tom Berg served on the local committee as Field Trips Chairman and coordinated the efforts in arranging the field trips and preparing the guidebooks. Assistant State Geologist Bob Van Horn chaired the Field-Trip Transportation and Logistics Committee. A major effort was devoted to production of guidebooks for the trips. The Survey's Technical Publications staff—Merrianne Hackathorn, Ed Kuehnle, Mike Lester, Bob Stewart, and Lisa Van Doren—spent many long hours getting the guidebooks ready for publication. Numerous other staff members assisted the Technical Publications staff in the guidebook effort.

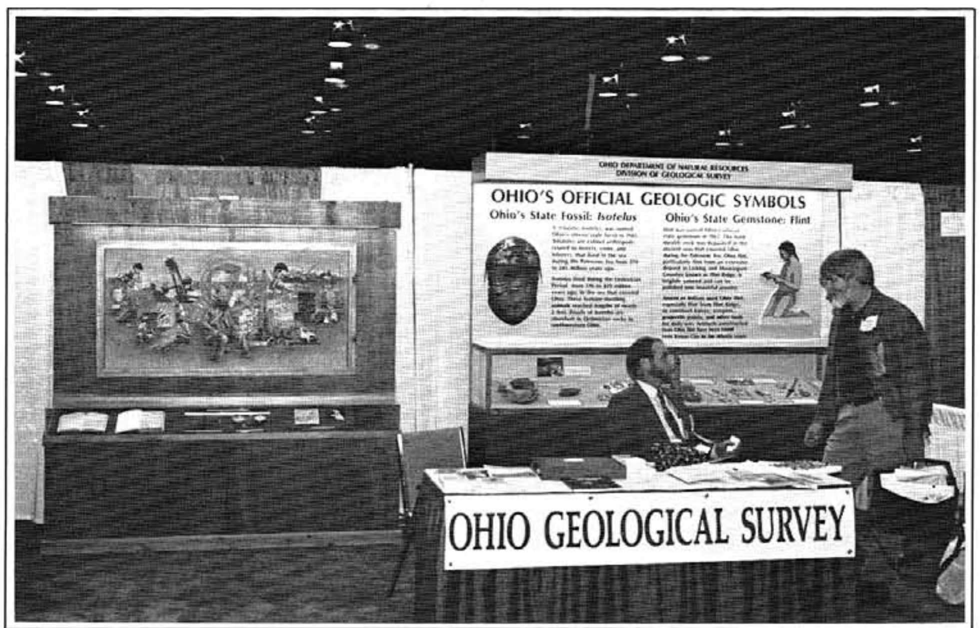
The guidebooks for many of the meeting field trips were "preprints" for trip participants. Publication of these guidebooks is now underway. An announcement of availability and cost will appear in a future issue of *Ohio Geology*.

Several Survey geologists were directly involved with the GSA field trips as leaders or co-leaders. Doug Shrake led a half-day trip to Caesar Creek State Park to collect Ordovician fossils; Ernie Slucher was a co-leader on a trip that examined stratigraphy and depositional environments of Pennsylvanian rocks in Ohio and Kentucky; Scott Brockman was a co-leader on a trip that examined Pleistocene geology in southwestern Ohio and adjacent portions of Indiana. Greg Schumacher contributed articles for two field trips, one on the type Cincinnatian and one on Kentucky geology. Sherry Weisgarber and Allan Axon served as leaders for a middle school "Science Day" at Caesar Creek State Park.

The Survey's booth in the Exhibition Hall was a popular place during the meeting. Two exhibits were featured in the booth. One was a new display module that features an original painting by Tim McGinnis of Phoenix, Arizona. The painting is a montage of images that depict the Survey's many activities and responsibilities and the long historical tradition of the organization. The second exhibit was the "Ohio's geologic symbols" display, which features flint (official state gemstone) and *Isotelus* trilobites (official state fossil). Two large specimens of *Isotelus* that exhibit predator-inflicted wounds (see accompanying article) attracted considerable attention at the meeting. Survey publications were distributed by a host of staff geologists who volunteered to serve a shift or two in the booth. Ohio Department of Natural Resources Director Frances S. Buchholzer and Deputy Director Sally T. Prouty attended the meeting and participated in a welcoming reception for outstanding geology seniors from across the nation.

Several Survey geologists presented papers or posters at the meeting. Rick Pavey, Dennis Hull, Scott Brockman, and Bob Van Horn exhibited a hand-colored prototype of the forthcoming Quaternary map of Ohio, which was largely assembled by the late Richard P. Goldthwait. Greg Schumacher, Mac Swinford, Glenn Larsen, Doug Shrake, and Ernie Slucher presented a poster session on the Survey's statewide bedrock-mapping program being done in cooperation with the U.S. Geological Survey. Larry Wickstrom was a co-organizer of a symposium on Precambrian rifting of the North American craton; he and Doug Shrake gave papers. Wickstrom and Jim McDonald presented a poster session on new digital cross sections of the subsurface being compiled at the Survey. Greg Schumacher and Dick Carlton (and others) gave a paper on correlation of Ordovician bentonites. Scudder Mackey presented a poster session on alluvial stratigraphy models. Tom Berg presented a paper on periglacial, proglacial, and preglacial deposits of southeastern Ohio.

Nearly the entire Survey staff was involved with one aspect or another of the GSA meeting and all performed collectively with an effort that was above and beyond the call of duty. The national geological community was given a positive impression of the state and its geological survey.



Division of Geological Survey display booth at the 1992 Geological Society of America meeting in Cincinnati. Dennis Hull, Head of the Regional Geology Section, talks with Charles Mason of Morehead State University.

CONFERENCE ON THE ENVIRONMENT

EnviroLink 1993, Governor's Conference on Ohio and the Environment: Partnerships for the Future, will be held on June 14 at the Radisson Airport Hotel, Columbus. The full-day conference will feature sessions on pollution prevention, ecosystems, stewardship, and working together.

On June 15, a series of optional, day-long field trips are scheduled. EnviroLink is coordinated by the Ohio Department of Education, Ohio Department of Natural Resources, Ohio Environmental Protection Agency, Ohio Alliance for the Environment, Ohio Chamber of Commerce, and Ohio Conservation and Outdoor Education Association. Funding for EnviroLink 1993 is provided by the Ohio Environmental Education Fund, a program of the Ohio Environmental Protection Agency.

The cost for the one-day EnviroLink 1993 program, including the luncheon and conference materials, is $45.00. Costs for optional field trips vary. For registration materials and additional information, please contact Irene Probasco, Ohio Alliance for the Environment, 445 King Avenue, Columbus, OH 43201. Telephone: 614-421-7819.

UPCOMING EVENTS

April 30-May 2, 1993—Ohio Academy of Science Annual Meeting. Youngstown State University. Contact: Ohio Academy of Science, 1500 W. Third Ave., Suite 223, Columbus, OH 43212.

May 1-2, 1993—Cincinnati Gem-Mineral-Jewelry Show, sponsored by the Cincinnati Mineral Society. Cincinnati Gardens, 2250 Seymour Ave., Cincinnati. Contact: Chris Parrett, 3811 Drake Ave., 1st Floor, Cincinnati, OH 45209.

HANDLING CHARGES REVISED

Handling charges for Survey publications and maps have been revised effective January 4, 1993. These charges cover the cost of postage and packaging for mail orders and have not been revised since 1984 despite several cost increases during this period.

Total cost of publications	*Handling charge*
less than $10.01	$2.00
$10.01 - $20.00	$3.00
$20.01 - $50.00	$5.00
$50.01 - $100.00	$8.50
more than $100.01	$10.00

The first 10 free items will be mailed at no charge. For each additional 10 free items (or fraction thereof) please include $1.00 for postage and handling. Additional cost for a mailing tube is still $1.00. Please contact the Survey for handling charges on shipments to foreign countries.

QUARTERLY MINERAL SALES, APRIL—MAY—JUNE 1992

compiled by Sherry L. Weisgarber

Commodity	Tonnage sold this quarter[1]	Number of mines reporting sales[1]	Value of tonnage sold[1] (dollars)
Coal	6,582,437	136	$182,329,928
Limestone/dolomite[2]	13,442,242	97[3]	48,277,635
Sand and gravel[2]	11,085,277	222[3]	38,132,015
Salt	559,296	5[4]	8,722,801
Sandstone/conglomerate[2]	414,769	24[3]	7,717,824
Clay[2]	332,560	27[3]	1,189,659
Shale[2]	650,565	22[3]	897,259
Gypsum[2]	42,687	1	405,527
Peat	5,923	3[3]	69,465

[1]These figures are preliminary and subject to change.
[2]*Tonnage sold* and *Value of tonnage sold* include material used for captive purposes. *Number of mines reporting sales* includes mines producing material for captive use only.
[3]Includes some mines which are producing multiple commodities.
[4]Includes solution mining.

QUARTERLY MINERAL SALES, JULY—AUGUST—SEPTEMBER 1992

compiled by Sherry L. Weisgarber

Commodity	Tonnage sold this quarter[1]	Number of mines reporting sales[1]	Value of tonnage sold[1] (dollars)
Coal	6,780,114	129	$191,043,825
Limestone/dolomite[2]	14,689,152	96[3]	53,820,966
Sand and gravel[2]	13,134,079	205[3]	43,984,686
Salt	841,704	5[4]	12,626,735
Sandstone/conglomerate[2]	371,025	19[3]	6,853,640
Clay[2]	643,199	26[3]	2,417,414
Shale[2]	367,035	22[3]	672,295
Gypsum[2]	59,617	1	566,362
Peat	5,566	3[3]	48,166

[1]These figures are preliminary and subject to change.
[2]*Tonnage sold* and *Value of tonnage sold* include material used for captive purposes. *Number of mines reporting sales* includes mines producing material for captive use only.
[3]Includes some mines which are producing multiple commodities.
[4]Includes solution mining.

SURVEY STAFF CHANGES

COMINGS

Sharon L. Stone, Executive Secretary, Administration Section.

EDITOR'S NOTE

Because of a multitude of circumstances, we have combined the Fall 1992 and Winter 1993 issues of *Ohio Geology*. We thank the many loyal readers of this publication for their indulgence and we will strive to produce future issues in a timely manner.

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