Ohio Geology

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Mine Subsidence: Mitigating that Sinking Feeling

By Christopher P. Gordon

Imagine waking in the middle of the night to the creaking of your home's foundation and the next day, finding massive cracks along the side of your house. Those of us that do not live in the coal-mining region of Ohio might be unfamiliar with abandoned underground mines and the potential dangers they present to buildings and infrastructure. But for over 650,000 Ohio homeowners, the threat of mine subsidence is all too real.

Over 4,300 underground mines have been abandoned throughout Ohio, accounting for almost 800 square miles of land (roughly four times the size of Columbus). As can be easily seen on the new *Known Abandoned Underground Mines of Ohio* (Map EG-3, details on page 6), the vast majority of these mines are located in the eastern, coal-mining region of the state; a few western counties have a history of mining other mineral commodities, such as gypsum and limestone.

Recently, through the use of Geographic Information System (GIS) technology, the Ohio Geological Survey has been able to more accurately locate these mines and provide an avenue for the public to view their recorded locations. By utilizing a Web-based Abandoned Underground Mine Locator, current homeowners, future homeowners, developers, and others can locate underground mines on or near residential and business properties.

Ohio mining: A brief history

In "Coal-mine subsidence in Ohio," Richard M. DeLong notes that for over 150 years, "underground mining of coal has been an active industry in eastern Ohio . . . [and has] left us with both a tradition of mining and a legacy of abandoned mines from the 'pick and shovel' era. Now, with an expanding population and its demand on space, the problems inherent in this legacy of abandoned underground mines are being realized."

The coal industry's role in driving America's Industrial Revolution cannot be exaggerated. Today, coal accounts for almost 90 percent of the electricity generated in Ohio, but its use as an inexpensive alternative to wood-burning furnaces led to the expansion of what was initially a very modest industry.

When underground mining of coal first began, large excavating equipment was not available to mining companies. A coal-mining company in the nineteenth century typically consisted of a few men with pickaxes and shovels. After discovering an outcrop of coal along a hillside, miners would begin cutting their way into the hillside via a horizontal or drift entry. If they were unable to gain access to a coal bed by drift entry, two other entry techniques could be used. Slope entries and shaft entries were both utilized to access coal that did not crop out at the surface.

Upon entry, two methods exist to extract coal: the room-and-pillar and longwall methods.

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An underground coal mine at Glouster in Athens County, operated by the Buckingham Coal Co., Inc., features two drift entries (left and center) and an air vent (right). Photo by Mike Williams.

OHIO ROCKS!

Larry Wickstrom,
Division Chief and State Geologist

You may have noticed this issue of *Ohio Geology* is in full color (previously it was only two-color). We were able to afford this change by making savings and eliminating costs in other areas of production. Some may wonder why we don't just publish this newsletter electronically as so many others are now doing. We have surveyed our readership and staff on this matter and find that the printed version is still preferred, though an electronic version is also available on our Web site.

During these trying economic times, I want to assure Ohioans that this agency is committed to constantly improving our service while finding and implementing new cost-saving measures. In fact, even though Ohio's geological survey is less than one-half the size of our surrounding neighbor states—the very states we compete against for many economic development projects—we are still a contender.

The Ohio Geological Survey prides itself on being an unbiased source of geologic knowledge for use by all in our state and houses the state's largest archive—open to the public—of data and maps concerning Ohio's geology. Our staff relies on this historic information and conducts original research to produce new information and create a wide array of detailed maps and reports. Frequently our work and our products support regulatory programs run by other state and federal agencies. Published reports, maps, and increasingly, online interactive maps and data assist local communities, solid waste districts and individual property owners in understanding their local geology and applying this information correctly. The Survey prudently performs its tasks behind the scenes, often in support of those making headlines. It is the nature of our work. Those who regularly use our products and services would agree that Ohio residents and industries that pay taxes in support of the Survey get a great return for their small investment.

As Ohio struggles to build a new economic future, much of that development will depend on the wise use of our geologic resources. Geologic issues of resource exploration and geohazards, such as abandoned underground mines, continue to become more acute. Geologic sequestration of carbon dioxide is a huge issue for the future of many industries and especially for coal-fired electric utilities. Commercial-scale wind turbines are fairly large structures and good geologic knowledge is needed to site them properly. To lessen our dependence on foreign energy sources, we will need to develop more of our domestic fossil fuels in the short term. Geologic information provided by the Survey, both historic and modern, speeds exploration and assists in expansion of production. The list goes on and we haven't touched on the environmental issues, such as the REX pipeline discussed later in this issue.

In short, the future of Ohio's economy relies on many industries and initiatives being successful. A strong state geological survey is necessary to provide underlying information and services essential for the success of many of these ventures.

Bedrock Geologic Map of Ohio *Now Available in Digital and Page-Size Formats*

Geologists, educators, land-use planners, and others interested in the state's earth science can now obtain a digital version of the Ohio Geological Survey's *Bedrock Geologic Map of Ohio* (winner of a 2008 Association of Earth Science Editors Award for Outstanding Publication). Map users will be able to overlay numerous geographic information system (GIS) layers available on the CD, such as bedrock formation contacts and faults, over their own unique digital map datasets. The *Bedrock Geologic Map of Ohio* (Map BG-1) CD-ROM and paper wall map are available for $25 or $15, respectively, plus sales tax and shipping. Please see ordering information on page 8.

A page-size (8½" x 11") version of the map also is available for download and printing on the Geological Survey Web site at <www.ohiodnr.com/geosurvey/>.

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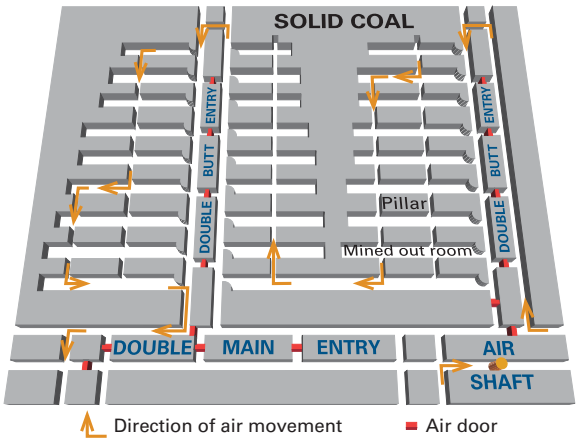
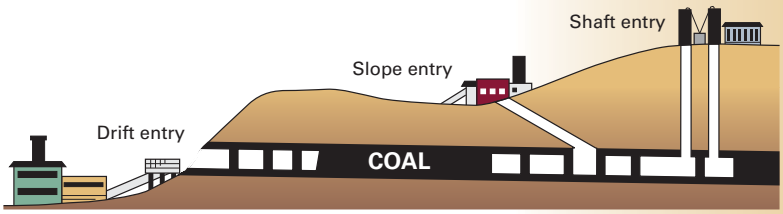
The oldest and still most prominent method of underground coal mining in Ohio is the room-and-pillar method. Miners cut double main entries to allow air to circulate through the mine. Rooms were then cut out perpendicular to these main entries. To prevent mine collapse, miners would leave pillars of coal in place to support the roof of the mine. Before abandoning a mine, they excavated as much coal as they could from the existing pillars without jeopardizing safety. A typical room-and-pillar operation extracts about 50 percent of the coal, leaving the rest in place for support. Miners would abandon a mine when the coal got too thin, the roof started to collapse, or the mine was no longer economically viable to operate.

But upon retreat from a particular mine, some miners practiced what is known as "pillar robbing" or "retreat mining." The pillars that were used to support the roof of the mine would be made dangerously thin for financial gain. Even with pillar robbing, no more than 70 percent of the coal was extracted. Nonetheless, pillar robbing greatly increases the risk of subsidence because of large unsupported areas.



This plan shows an idealized layout of a double-entry room-and-pillar mine (modified from Crowell, 1995).

As the coal industry developed, along with the advancement of technology used for mining coal, operations grew and mines became more expansive. It wasn't until after World War II that another form of underground mining, longwall mining, developed for coal extraction within the United States. In contrast to room-and-pillar mining, longwall mining involves extracting a rectangular panel of coal with a consistent thickness. Miners use hydraulic roof supports to prevent the roof from caving. Longwall mining extracts approximately 60-70 percent of the coal within a mine. Typically, longwall mining causes surface subsidence almost simultaneously and therefore, does not factor into future subsidence issues. Owing in part to the inconsistent thickness of the coal in many parts of Ohio, room-and-pillar mining continues to remain the predominant method for underground mining of coal.



Three mine opening types grant access to underground coal mines: Drift entries use a horizontal opening to mine coal found above stream level; shaft entries use a vertical opening; slope entries use an inclined opening to reach coal at great depth or below stream level.

What is mine subsidence?

Subsidence is a lowering of the earth's surface due to collapse of either bedrock or unconsolidated materials or both into an underground void. Even the slightest change in surface elevation can affect the integrity of overlying buildings, roads, pipelines, sewer systems, and water wells. Two types of mine subsidence are prevalent in Ohio: pit subsidence and sag or trough subsidence.

A pit subsidence is caused by a mine roof collapse (usually between pillars or an abandoned shaft) eventually working its way to the surface and manifests as a relatively small (typically less than 40 feet across) circular depression with steep sides. A trough subsidence forms as a broad dip in the surface that can be spread over a number of acres after pillars collapse or punch into the underclay from the weight of the overlying strata. Neither type of subsidence happens overnight. It might take tens or even hundreds of years for a mine roof collapse to occur and make its way to the surface.

Predicting the unpredictable

Over the past several decades, underground mine subsidence has become increasingly acute because of the aging support beams, rock bolts, and pillars of abandoned mines and the increasing encroachment of development into old mining areas. This heightening threat on Ohio's infrastructure is evident by the time and expense given in recent years towards the repair and research of mine subsidence. During 2008, the Ohio Department of Natural Resources (ODNR),

This road collapsed into an abandoned underground mine only hours after road repairs fixed a minor dip. Photo courtesy of Tom Reed.

Division of Mineral Resources Management (DMRM) Abandoned Mine Land–Emergency Program invested more than $1.3 million to complete 32 projects related to underground mine subsidence. As of 2005, the Ohio Department of Transportation had spent an estimated $14.3 million to repair state and federal highway damage caused by mine subsidence.

A number of factors contribute to mine subsidence. The depth from ground level to the mine, height of the mine, extraction method, characteristics of overburden (the material between the earth's surface and the roof of the mine), and groundwater table fluctuations can all contribute to the cause of a subsidence. Unfortunately, a modern investigation model to predict subsidence has not been funded in Ohio.

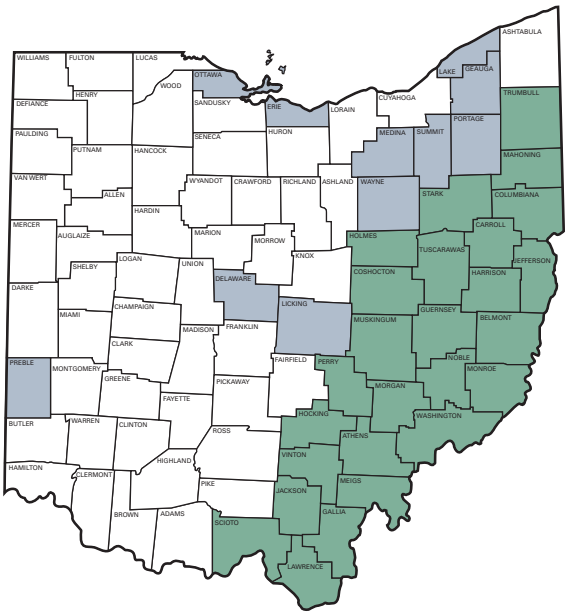
While some of these factors are difficult to quantify, others can be compiled into a useful dataset to help determine the potential for collapse. After locating a mine using GIS, geologists can start to build a three-dimensional model characterizing the existing conditions surrounding the mine. Mine elevations are typically captured from the abandonment map and verified after locating the mine's entry elevation in relation to topography. Drilling records in the vicinity of a mine give geologists information such as the ratio of bedrock to unconsolidated material, as well as the physical properties of these materials, over a particular mine—if the ratio is small and the materials are less competent, the more likely a mine will collapse. Compiling critical geologic datasets, such as surface, bedrock, and mine elevations, and past subsidence incidents, will allow geologists to begin to quantify potentially hazardous areas.

Insurance coverage for homeowners

Damage from mine subsidence can be devastating. Underground mine collapse can cause tens of thousands of dollars in damage to a home. Worse, the property could be deemed unfit for residence.

The amount of money spent on damages caused by underground mines is staggering, and the thought of purchasing a house near an underground mine without knowing if or when a subsidence will occur is troubling. Fortunately, Ohio residents are afforded some peace of mind. The Mine Subsidence Insurance Program, enacted by the Ohio Legislature in 1985, created the Mine Subsidence Insurance Governing Board, the Mine Subsidence Insurance Fund (MSIF), and the Ohio Mine Subsidence Insurance Underwriting Association (OMSIUA). Many of Ohio's counties require a mine subsidence policy to be included in the homeowner's insurance policy or offered as an option, and each year about 650,000 of these policies are written by members of the OMSIUA.

If you reside in one of these counties, you are protected (up to $100,000 or the amount of insurance on the dwelling, whichever is less) from any structural damages to your home because of mine subsidence (only dwellings for 1–4 families are covered by insurance). The annual premiums are placed directly into the MSIF and are used to provide funding for subsidence mitigation and renovation projects.



Mine subsidence insurance coverage by county.

Building an information database

Even though geologists cannot yet predict when or if a subsidence event will occur at a given location, they can begin to classify whether a subsidence is *likely* and whom it might affect. Knowing locations of abandoned underground mines helps to better understand the factors associated with mine subsidence. Through various funding sources, the Geological Survey has georeferenced all of Ohio's abandoned underground mine maps. Georeferencing a mine map consists of taking a scan of a mine map, adjusting it to scale, and placing it in its known location using GIS software. For example, an abandoned mine map might have been originally drafted using land subdivision boundaries and road intersections as reference points. If those reference points still exist, the mine map can be properly scaled and placed in its known location. In addition, spatially locating a mine map assists filling in missing information such as mine elevation. The georeferencing process is necessary to help visualize what lies below Earth's surface and in turn, develop a system to rate areas on their susceptibility to subsidence.

In 2004, the Geological Survey, along with the OMSIUA and the DMRM, released an interactive Web site designed to improve public access to abandoned underground mine records. These records include not only the original abandonment maps turned into the state upon closing of the mine but also details about the mine. Such information can aid in quantifying and categorizing the hazard potential and includes but is not limited to the commodity being mined (limestone, gypsum, coal, clay, etc.), past operator(s) of the mine, the years of operation, and any notes about the condition of the mine when abandoned, such as roof collapse. All of the information found on the maps and accompanying documents are compiled into an abandoned underground mine database, which has been made available to the public on the Geological Survey's Web site. The Web site contains an address locator system and displays aerial photography and topographic maps as references. Users can view and download digital versions of the mine maps from the Web site.

Continuing data development

When abandoned mine map scanning first began in the 1990s by the U.S. Office of Surface Mining, digital storage space was cost-prohibitive and technology systems could handle only a relatively small file size by today's standards. Consequently, the original scans currently on the Web site are of relatively poor quality. Fortunately, through the development of scanning technology and virtual storage space improvement, the Geological Survey is in the process of scanning all of the original paper abandonment maps at higher resolution [400 dots per inch (DPI)] and uploading them to the Web site. High-resolution scanning of original abandonment maps will provide users with more detailed images and nearly an exact replica of the original maps. Although the Web site has been recently updated to improve usability, the Geological Survey acknowledges that compiling geologic data to upgrade the amount of information available is an ongoing process, and it is committed to improving public access to abandoned underground mine records and enhancing the quality and quantity of the data presented on the Web site.

Conclusion

Ohioans who live in one of the 650,000 homes that have mine subsidence insurance may sleep a little more soundly knowing that they are financially protected from mine subsidence-related damage. If you are a current or potential homeowner in one of the counties in which mine subsidence insurance is available, or simply are curious, please be sure to check the Geological Survey's Web site to gain a better understanding of the hazards created by abandoned underground mines. If you have any questions regarding your subsidence insurance coverage, please contact your insurance provider or visit < www.ohiominesubsidence.com > .

Ohio's abandoned underground mines account for almost 800 square miles of land, about four times the size of Columbus.

Further Reading

DeLong, R.M., 1988, Coal-mine subsidence in Ohio: Ohio Department of Natural Resources, Division of Geological Survey, Ohio Geology, Fall, p. 1–4.

Crowell, D.L., 1991, Drilling for mine subsidence mitigation, *in* 1990 Report on Ohio mineral industries: Ohio Department of Natural Resources, Division of Geological Survey, p. 5–11.

Crowell, D.L., 1995, History of the coal-mining industry in Ohio: Ohio Department of Natural Resources, Division of Geological Survey Bulletin 72, 203 p.

Crowell, D.L., 2001, Mine subsidence: Ohio Department of Natural Resources, Division of Geological Survey GeoFacts 12.

Crowell, D.L., 2005, History of coal mining in Ohio: Ohio Department of Natural Resources, Division of Geological Survey GeoFacts 14.

OMSIUA, 2007, Annual Report: Ohio Mine Subsidence Insurance Underwriting Association, 10 p., accessed at < http://www.ohiominesubsidence.com/AnnualReport.aspx > .

New Abandoned Underground Mine Map

The new *Known Abandoned Underground Mines of Ohio* (Map EG-3) shows that known abandoned underground mines (AUMs) are located in approximately half of Ohio's 88 counties. Most of the mines are located in the historic coal and clay mining districts of eastern and southeastern Ohio. The map can help Ohio citizens determine if they're living, working, or building above AUMs. *Known Abandoned Underground Mines of Ohio* can also be used to determine if AUMs might adversely affect new underground mine operations, or water, oil, and natural gas wells.

Data used to create the map were also used to create ODNR's free AUM Interactive Mapping System (IMS). Internet users can enter a street address into the IMS and check for AUMs near the property. The Web site can be accessed at < www.ohiodnr.com/geosurvey/ > . The Ohio Geological Survey and its partners continue to search for records of what could be thousands of historic underground mines that were never reported to the state.

The wall map and associated text are available in paper form for $15 plus sales tax and shipping. Please see ordering information on page 8.

The Rockies Express Pipeline Comes to Ohio

The massive Rockies Express Pipeline (REX) is but one small part of the solutions our nation needs for reliable, clean, reasonably priced energy. The 1,679-mile REX pipeline, scheduled for completion in 2009, will be capable of transporting nearly 1.8 billion cubic feet per day of natural gas extracted from the Rocky Mountain states of Colorado and Wyoming to the banks of the Ohio River at Clarington, Ohio, in Monroe County. When combined with the many interconnections to existing natural gas pipelines, the REX pipeline will be part of one of the largest natural gas distribution systems in the world. Planned future construction of additional pipelines radiating from Clarington will transport natural gas to Mid-Atlantic and New England States. The price tag for the REX project is projected somewhere between six and eight billion dollars.

Throughout southern Ohio in 2009, thousands of 40- to 80-foot sections of 42-inch-diameter, high-quality, steel pipe will be welded together to create this pipeline. The pipeline will be lowered into the trench and buried with subsoil and then topsoil. To ensure that no leaks are present, crews will flood the pipeline with water and pressurize it beyond normal operating pressures. The final step is restoring the area to its original condition and marking the boundaries of the 50-foot wide permanent easement.

Before a single segment of pipe is moved into place, the REX pipeline project will have undergone rigorous permitting processes, held numerous public open houses and forums, participated in countless meetings with state and local governments, and negotiated acquisition of right-of-ways to ensure the pipeline construction is safe and environmentally sound.

Those opposed to the REX pipeline were provided with opportunities to express their concerns and solutions were discussed and often reached. Opposition to the pipeline centered around potential impacts on sensitive environments, such as streams and wetlands, and the rights of individual property owners.

Early in the planning process, the Ohio Geological Survey provided REX officials and contractors with basic geologic information in the form of maps showing bedrock geology, depth and elevation of bedrock, and thickness of stream and river valley sediments. ODNR officials met with REX representatives to express concerns about the REX pipeline crossing under the State and National Scenic Rivers located in southern Ohio. As a result, staff geologists were on site during the horizontal directional drilling (HDD) under the Little Miami and Big Darby State and National Scenic Rivers and under right-of-ways crossing Caesar and Deer Creeks, in Caesar Creek and Deer Creek State Parks, to monitor any potential problems with the HDD drilling.

The main concern of the ODNR was to reduce the environmental impact of any drilling fluids that could escape through drilling-induced fractures of the surrounding bedrock and valley-fill sediments. The escape of these drilling fluids is referred to as a *frac-out.* The frac-out of drilling fluids could enter the na-

tional scenic rivers and streams along the REX pipeline right-of-way, particularly at times of low flow, and have a deleterious impact on protected species of mussels, fish, and other aquatic creatures. Staff geologists were on site to monitor drilling progress and any frac-outs and, if frac-outs occurred, to notify appropriate agencies and officials so that containment and mitigation efforts could be quickly undertaken. Once HDD drilling is completed at each National Scenic River crossing, the REX pipeline is safely protected by a buffer of some 50 to 200 feet of solid bedrock between the stream bed and the top of the pipeline.

The impact of the REX pipeline project on the U.S. economy is as yet uncertain. In the next decade, some energy experts predict that demand for natural gas in the United States could increase by over 50 percent. Natural gas—the cleanest-burning fossil fuel and one of the most abundant domestic energy sources—is easy and safe to transport through pipelines and could lessen dependence on foreign oil supplies. But the lack of new pipelines to transport this commodity to market is a major drawback to its utilization. Thus, the REX and other future pipelines may be one solution to the growing demand for clean, reliable, domestically produced energy in the United States.

—Gregory A. Schumacher and Michael P. Angle

Editor's Note: Please do not trespass on REX pipeline property or the private property of adjacent landowners. For additional information about the Rockies Express Pipeline, please visit <http://rexpipeline.com>.

The Rockies Express stretches from Rio Blanco County, Colorado, to Monroe County, Ohio.

Douglas J. Mullett, 1956–2009

With deep regret we announce that one of our own has passed: Geologist Doug Mullett lost a courageous battle with Mantle Cell Lymphoma on January 5, 2009, at the age of 52. Doug was employed by the Ohio Geological Survey as the supervisor of the Energy Resources Group from February 2007 until his death. While Doug may not have been at the Geological Survey long, he always had a positive attitude and made a huge impact on the lives of our staff.

After receiving his B.S. degree from Mount Union College in 1978, Doug went right to work in the Ohio oil field, first for Appalachian Exploration in Gnaddenhutten, then on to New Frontier Exploration in North Canton. He returned to school and received his M.S. in Geological Sciences from Wright State University in 1981. Doug then joined Cities Service in Tulsa, Oklahoma, from 1981 through 1985 when he returned to Ohio to work for Lomak Petroleum in Hartville. In 1986, Doug returned to school once again, this time to Kent State where he pursued a Ph.D. and was employed as a geology instructor through 1991.

Doug changed course in 1991 by entering the environmental geology field where he remained for the next sixteen years. In Michigan, Doug worked for five different firms, always at increased responsibility levels, and handled work including tank removals, RCRA regulation support, superfund site remediation, and staff and contractor supervision. He was beloved by his co-workers. In 2007, Doug found his "dream" job. He was thrilled to be working for the Ohio Geological Survey and we were thrilled to have him on our team.

Doug leaves behind his loving wife, Judy Cerett-Mullett. He was the extremely devoted father of Trevor, Brock, Chase, and Cole; son of Myron and Phyllis (Rupp) Mullett of Alliance, Ohio; and brother of Vicki (Greg) Vasto, Pam (Bruce) Hickinbotham, Cindy (John) Donelan and the late Greg Mullett.

Active in numerous organizations, including the Boy Scouts of America, the American Association of Petroleum Geologists, the Ohio Academy of Science, and the American Institute of Professional Geologists, Doug will be remembered for his kindness, gentle soul, generosity, and devoted love for his family.

Donations may be made to the Mullett Boys Education Fund, c/o Citizens First Bank, 33205 Grand River Ave., Farmington, MI 48336.

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Al Walker, Ohio Ground-Water Geology Pioneer

On February 4, 2009, we were saddened to hear about the passing of Alfred C. "Al" Walker, the longtime head of the Water Inventory Section of the ODNR, Division of Water, and truly one of the founding fathers of ground-water geology in Ohio. In October 2001, Al and long time associate James J. "Jim" Schmidt were both recipients of the Geological Survey's Mather Medal, a prestigious award recognizing lifelong contributions to knowledge of Ohio geology.

After serving as an Army Air Corps bombardier during World War II, Dennison, Ohio, native Al Walker earned a B.S. in geology from Marietta College. Thereafter, he worked for the Kansas Geological Survey and as a ground-water geologist at the Virginia Geological Survey.

In 1953, Al returned to Ohio to head the ODNR, Division of Water, Water Inventory Section. Al worked on establishing a series of county-based ground-water bulletins and learning both the background geology and nature of ground water in Ohio. In 1962 under Al's guidance, Ohio became one of the first states to complete ground-water availability mapping for the entire state, which was developed upon a watershed basis. Al then turned his attention toward Ohio's buried valley and limestone aquifers.

Al also was an early pioneer in Ohio ground-water chemistry and water contamination issues. Shortly after the formation of the Ohio EPA in 1972, the Division of Water was temporarily disbanded and the Water Inventory Section became part of the Geological Survey, until 1976 when the Division of Water was reestablished. Al began a series of county-based ground-water resources maps, completed in 1996.

Al retired in January 1986, but continued to work part-time, finishing numerous ground-water resource maps and other projects. Together with Jim Schmidt, Al authored 142 publications on Ohio ground-water resources, a remarkable legacy.