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The Marcellus Shale: Resources and Reservations

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The Marcellus Shale is an organic-rich, sedimentary rock formation in the Appalachian Basin of the northeastern United States that contains significant quantities of natural gas. Published estimates of the amount of gas that may be recoverable from the Marcellus Shale have been higher than 1.42 trillion cubic meters, or 50 trillion cubic feet [*Engelder and Lash,* 2008]. The recovery of commercial quantities of gas from a low-permeability rock like the Marcellus became economically possible with the application of directional drilling technology, which allows horizontal boreholes to penetrate kilometers of rock, combined with staged hydraulic fracturing to create permeable flow paths into the shale. Each hydraulic fracturing treatment may use more than 11 million liters of water (3 million gallons), which must then be recovered from the ground to allow gas flow [*Harper,* 2008].

The Marcellus Shale may contain enough gas to support the drilling of thousands of new wells. However, water resources agencies and concerned citizens throughout the Appalachian Basin have raised questions about the possible environmental effects of shale gas development on watersheds, groundwater, and ecological habitat. The recent oil spill disaster in the Gulf of Mexico following the 20 April explosion of the Deepwater Horizon drilling platform has encouraged the producers of onshore resources to pursue additional opportunities, potentially leading to even greater activity in the Marcellus Shale. At the same time, heightened public awareness from the Gulf oil spill has increased the scrutiny of all drilling, including shale gas.

A Significant Gas Resource

The Marcellus Shale extends from the southern tier of New York State to half of Pennsylvania and most of West Virginia and occurs in parts of western Maryland; Virginia; eastern Ohio; and southern Ontario, Canada, underlying a land area of about 128,000 square kilometers (Figure 1). It forms the basal unit of a thick sequence of clastic sedimentary rocks from the Middle to Upper Devonian (390–360 million years ago) in the Appalachian Basin. The sediments were derived from highland areas in present-day New England. The black, organic-rich mud of the Marcellus Shale was emplaced as a relatively uniform layer across the basin, in anoxic and probably shallow water, prior to the influx of younger sediments. The Catskill Mountains in New York are the remains of a Devonian delta from the ancient river that deposited these younger sediments, and the Marcellus Shale is buried beneath them [*Schwietering,* 1979].

Organic matter in the shale was transformed into natural gas over geologic time as the buried rocks were subjected to heat and pressure. Free gas occurs in voids such as fractures and pores within the shale, and methane is also chemically adsorbed onto carbonaceous material [*Soeder,* 1988]. Estimates of the amount of natural gas that may be recoverable from the Marcellus Shale using modern production technology vary widely, from 60 billion cubic meters (2 trillion cubic feet), estimated by the U.S. Geological Survey (USGS) [*Milici and Swezey,* 2006], to more than 1.42 trillion cubic meters (50 trillion cubic feet) [*Engelder and Lash,* 2008]. USGS resource estimates are calculated using a "petroleum system model," in which organic content, thermal maturity, migration pathways, and reservoir properties are derived from production data. The current Marcellus drilling activity did not start until 2005, so only limited amounts of production data were available for the 2006 USGS estimate, resulting in the relatively low number.

Recent reports in the media suggesting that hundreds of trillions of cubic feet of gas might be recoverable from the Marcellus Shale have attracted the attention of federal, state, and local governments, landowners, and ordinary citizens. Petrophysical and petrologic investigations at the Department of Energy's National Energy Technology Laboratory (DOE/NETL) are attempting to constrain Marcellus Shale recoverable gas estimates. These studies are also expected to have applications to other shale gas resources, such as the Utica Shale in the Appalachian Basin and the New Albany Shale in the Illinois Basin.

New Production Technology

Commercial amounts of natural gas can be produced only from fine-grained rocks like shale through reservoir stimulation, which creates permeable pathways into the formation that allow gas to flow easily into a well. Effective reservoir stimulation in the Marcellus Shale uses "slick-water fracturing," which is a pressurized mixture of water, sand, and chemical additives that hydraulically fractures the rock.

In the mid-1970s, the DOE funded the Eastern Gas Shales Project (EGSP) to advance the commercial development of shale gas. A variety of reservoir stimulation techniques were used on shale wells with varying degrees of success [*Horton,* 1982]. A decade later, the Institute of Gas Technology performed laboratory measurements on several EGSP shale core samples using ultrasensitive core analysis equipment developed for tight gas sandstones. One of the samples analyzed was Marcellus Shale from the central part of the Appalachian Basin. This core had a porosity of about 10%, and gas permeability was in the microdarcy range, similar to dry, low-permeability gas sands. Additional laboratory measurements on the sample suggested that gas-in-place values for the Marcellus might be orders of magnitude higher than previously estimated [*Soeder,* 1988].

Low prices for natural gas and ineffective production techniques did little to advance shale gas production and use in the 1990s. However, improvements in drilling technology, specifically directional drilling, have led to economically feasible gas recovery from the Marcellus Shale. Directional drilling uses a steerable drill bit to penetrate long horizontal distances, sometimes thousands of meters, through the target formation. Because the shale formations are generally only 30–50 meters thick, drilling horizontal boreholes into the rock allows the wellbore to contact a much greater volume of shale compared with vertical drilling (Figure 2). The rock is fractured along these horizontal boreholes at intervals of a few dozen meters (hundreds of feet) by the hydraulic fracturing process, which applies fluid pressures in excess of rock strength to break open the rock. The hydraulic fractures extend deep

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into the formation, up to 300 meters (1000 feet) from the borehole, and provide high-permeability flow paths from the shale back into the horizontal well. After the completion of hydraulic fracturing, water is drained and pumped from the well, allowing gas to flow.

Shale gas production from horizontal wells is reported to be significantly greater than production from vertical wells. Using these drilling techniques, Marcellus Shale development has proceeded rapidly since the first horizontal well was completed in Pennsylvania in 2005.

Environmental Concerns

If not carefully allocated, the large withdrawals of water required for Marcellus Shale hydraulic fracturing can have impacts on local water resources. In addition, transporting bulk volumes of water, heavy equipment, and supplies to remote, rural drill sites over unimproved roads may degrade small watersheds and headwater streams with sediment and chemicals [*Soeder and Kappel,* 2009]. Drilling could also contribute to habitat fragmentation as landscapes, particularly forests, are crisscrossed with access roads connecting a patchwork of drill pads. Further, invasive species might be introduced as equipment and water supplies are brought in from distant localities. Concerns about landscape degradation have led New York City to oppose drilling in the watersheds of the upper Delaware River, where there is a significant potential for Marcellus Shale gas production, because the city receives its water supplies from those carefully managed watersheds. Problems of stray gas in aquifers near areas of active Marcellus Shale drilling, and the safe disposal of solids, are also issues of concern.

Perhaps the most visible environmental issue associated with Marcellus Shale gas production is the disposal of "flow-back" fluids. These consist of the recovered hydraulic fracture water, plus any deep groundwater from the formation itself. Processing these liquids for disposal can be problematic because of their high concentrations of total dissolved solids (TDS), which turn the water into brines [*Hayes,* 2009]. Most wastewater treatment plants are designed to remove suspended solids and generally do not treat TDS effectively. Several episodes of saltwater discharge into Appalachian rivers have been blamed on the improper disposal of Marcellus flow-back fluids.

Water and land use concerns have turned shale gas into a contentious and polarizing issue. On one side are gas producers and landowners who are eager to develop the resource, and on the other are environmental advocates urging caution. The speed at which the resource is being developed often forces regulatory agencies to make policy decisions based on little data. In the past, industry has been secretive about additives in the fluids used for hydraulic fracturing and the volumes of water recovered after each treatment. As a result, drillers are blamed for every

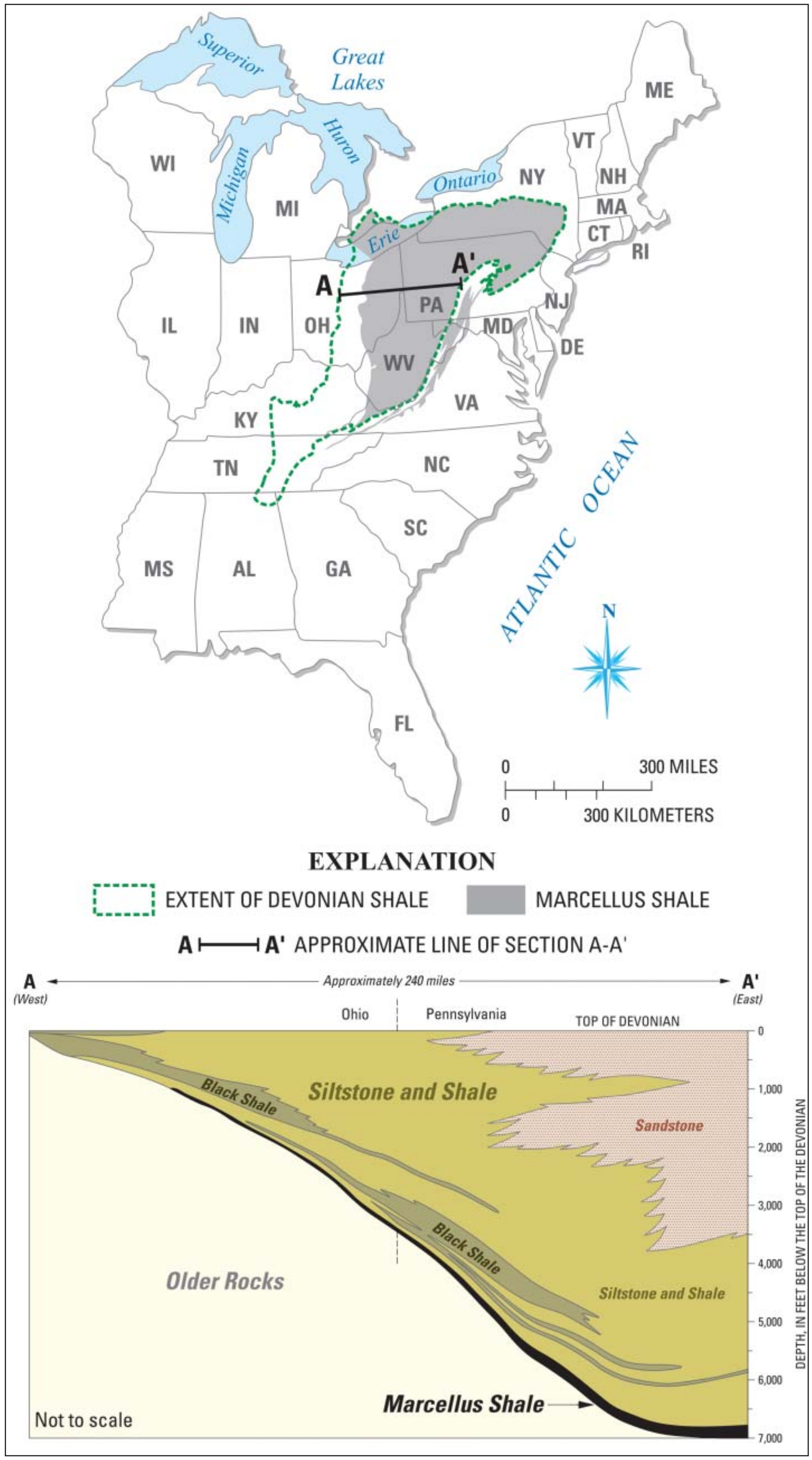

Fig. 1. Distribution of the Marcellus Shale in the Appalachian Basin of the eastern United States, with a simplified cross section shown along line A–A' (after Milici and Swezey *[2006] and* Potter et al. *[1980]).*

contaminant found in local groundwater, from pharmaceuticals to gasoline. To counter this, some industry leaders have begun publicly announcing the makeup of their fracturing fluids [*Range Resources,* 2010].

There are no basin-wide standards for brine analysis, so it is difficult to compare the small amounts of data that do exist. At present, the only attempt at a comprehensive study of flow-back fluid was undertaken in 2009 by the Gas Technology Institute (GTI). The work was performed for state environmental agencies and funded by an industry consortium, but the report [*Hayes,* 2009] has not been widely released. Fluid samples from 19 Marcellus wells were collected at 1, 5, 14, and 90 days after hydraulic fracturing and analyzed by a certified environmental laboratory following U.S. Environmental Protection Agency procedures. Concentrations of TDS ranged from 680 to 345,000 milligrams per liter and typically increased over time. The report concluded that shale gas flow-back water is chemically similar to the waters found within other Appalachian Basin rock formations. The cations in the flow-back fluid are dominated by sodium and calcium; the main anion is chloride; and metals such as iron, magnesium, and boron are at levels typical for deeply seated brines within the Appalachian Basin

A favored procedure for handling flow-back fluid is to treat the recovered brine on site and reuse it in another hydraulic fracture treatment, reducing disposal volumes. Pennsylvania requires wastewater treatment of flow-back fluid for surface water disposal. There are currently six industrial wastewater treatment plants in Pennsylvania equipped to handle brine. Rules in other states vary, and several are waiting to see how their neighbors fare before enacting their own standards. An alternative to wastewater treatment for flow-back fluid disposal is to inject it deep into the ground, although Pennsylvania has few favorable locations for deep injection sites. Several deep wells in southeastern Ohio have been used for this.

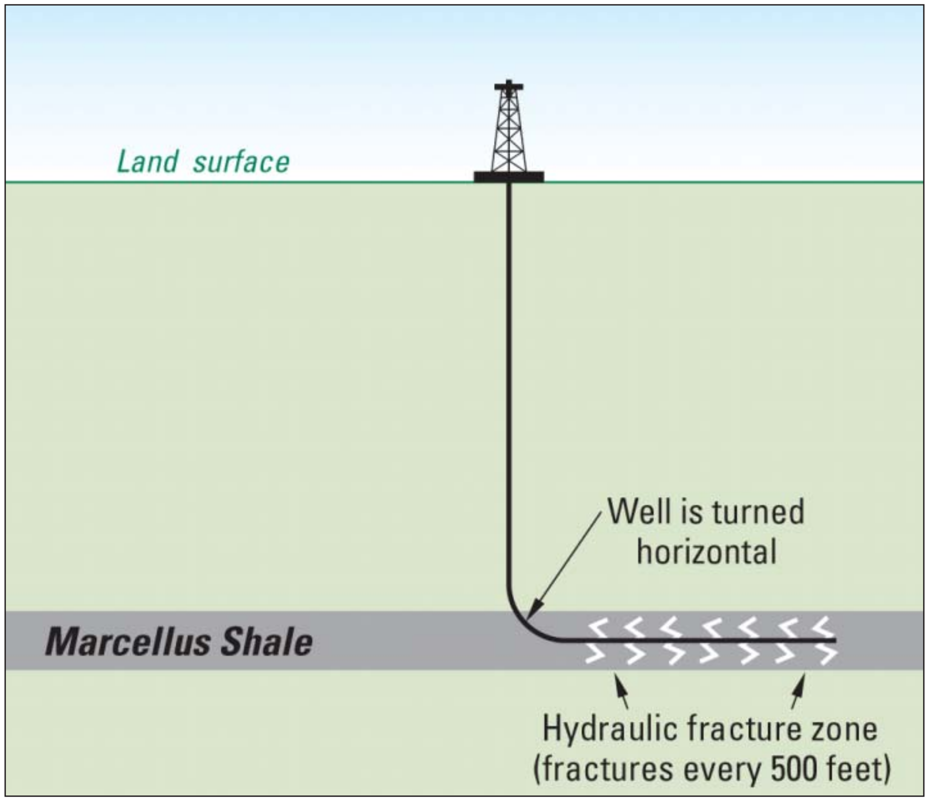

Fig. 2. Combination of directional drilling and hydraulic fracturing technology used for gas production from the Marcellus Shale in the Appalachian Basin [from Soeder and Kappel, *2009].*

New Efforts to Monitor Environmental Impacts

In cooperation with industry partners, the DOE/NETL is embarking on a research program with other federal and state agencies to monitor the environmental impacts of Marcellus Shale drilling (see the online supplement to this *Eos* issue; http://www.agu.org/eos_elec/). Plans include baseline ecological, hydrological, and air quality monitoring of a drill site for a year before the rig moves to the location, and then continued monitoring through the drilling, completion, and production phases of the well. If funding is available, the monitoring can be carried out on other wells in different land use settings and under different drilling techniques. Benefits are expected to include identification of the most sensitive environmental parameters, development of indicators for monitoring shale gas production, improved management practices for industry, access to rock and fluid samples for analysis, and a better definition of where regulatory agencies should focus their attention.

Gas producers and landowners with signed leases are eager to move forward and develop the potentially significant quantities of natural gas contained in the Marcellus Shale. At the same time, many environmental and civic groups are expressing concerns about possible land use changes and water disposal issues that may result from large-scale Marcellus gas drilling. Regulatory agencies are often caught in the middle. The Environmental Protection Agency has begun a series of public meetings to determine citizen concerns related to shale gas production. Coordinated research efforts by state and federal agencies are under way to provide data on resource assessments, production practices, and environmental impacts to all parties for informed, factual discussions and science-based regulatory decisions.

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