Marcellus shale play is located in the Appalachian basin and covers parts of New York, Pennsylvania, Maryland, and West Virginia.

Marcellus shale play is the one of three overlapping shale plays that includes the older Utica shale and the younger Devonian shales.
recurring episodes of black shale sedimentation during the Devonian
Marcellus Stratigraphy

Geophysical Log

Lash and Engelder (2009)
Geophysical Log

Marcellus Stratigraphy

Lash and Engelder (2009)
Darker gray = more organic rich

Smith (2010)

Beaver Meadows #1 Core

Darker gray = more organic rich

Highest TOC (up to 20%)
Seismic survey from Otsego County

Gamma log

Seismic image courtesy of Gastem
Shale Gas Development

- First commercial gas well in the United States was a Devonian shale gas well drilled in 1821 near Fredonia, NY

Site of first gas well in the United States
Marcellus Shale Gas Development
Hydraulic Fracturing and Horizontal Drilling

Source: Independent Oil and Gas Association of Pennsylvania
Hydraulic Fracturing

• First hydraulic fracturing of oil & gas well was in 1948

• Medina Sandstone, a tight gas reservoir, was extensively fraced in western New York and Pennsylvania during the 1970s

• 100,000 oil & gas wells are fraced per year
Horizontal Drilling

- First horizontal well was drilled in 1948
- First horizontal shale gas well was drilled in 1988 in the Antrim Shale, Michigan
- First horizontal gas well in New York was drilled in 1989

Trenton/Black River well

- Top of cement - 0 feet
- Bottom of conductor casing - 50 feet
- Bottom of surface casing - 1,000 feet
- Top of cement - 3,000 feet
- Bottom of intermediate casing - 6,750 feet
- Top of cement - 8,500 feet
- Bottom of production casing - 10,500 feet
- 4,000 foot long open-hole leg
Marcellus Shale Gas Development
Horizontal Drilling
at Multi-Well Pad Sites in Black Shale
Orthogonal joint sets
East-northeast trending J1 fractures and northwest-trending J2 fractures

Dual porosity gas reservoir where fractures drain rapidly and matrix drain slowly

Free gas and adsorbed gas in matrix

Connect matrix porosity to the wellbore by intersecting multiple J1 fractures

Drill horizontal wells to the north-northwest or south-southeast perpendicular to major horizontal stress and J1 fractures

Terry Engelder PSU
Multi-Well Drilling Pad Site With Six Horizontal Laterals

Horizontal Lateral

Drilling Pad
Multi-Well Drilling Pad Site With Six Horizontal Laterals

Minimizes surface disturbance but concentrates industrial activity
Top-set rig for drilling vertical surface- and intermediate-cased interval

Directional rig for drilling horizontal leg
Walking legs on directional drilling rig

Wellheads of first two of six horizontal wells

~15 ft
Horizontal wells target basal Marcellus Shale
Target horizon (Union Springs Shale) mapped using offset well logs and seismic.

Logging-while-drilling used to steer lateral within target beds.

Schlumberger (2010)
High TOC and elevated radioactivity in basal Marcellus Shale

<table>
<thead>
<tr>
<th>Location of the Core</th>
<th>Uranium Content (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allegheny, NY</td>
<td>8.9 – 67.7</td>
</tr>
<tr>
<td>Tompkins County, NY</td>
<td>25 – 53</td>
</tr>
<tr>
<td>Livingston County, NY</td>
<td>16.6 – 83.7</td>
</tr>
</tbody>
</table>

Levanthal and others (1981)
Uranium & Thorium to Radium & Radon
Radioactive Decay Series

**Uranium-238**
- Uranium
  - U-238, $4.49 \times 10^9$ y
- Thorium
  - Th-234, 24.1 d
- Actinium
  - Ac-228, 6.13 h
- Radium
  - Ra-226, 1622 y
  - Ra-228, 5.75 y
  - Ra-224, 3.64 d
- Radon
  - Rn-222, 3.825 d

**Thorium-232**
- Thorium
  - Th-232, $1.41 \times 10^8$ y
- Actinium
  - Ac-228, 6.13 h
- Radium
  - Ra-226, 1622 y
  - Ra-228, 5.75 y
  - Ra-224, 3.64 d
- Radon
  - Rn-220, 55 s

**EXPLANATION**
- Alpha decay
- Beta decay
- Radioisotope and half life
High TOC and abundant pyrite in basal Marcellus Shale

Lash and Engelder (2009)
Drill Cuttings

- Elevated uranium and abundant pyrite in high-TOC black shale
- Multi-horizontal well site will generate more than 500 times the volume of shale cuttings than single-vertical well site

Core of target interval

Drill cuttings
Drilling Fluids and Cuttings

- Lined pit
- Closed-loop system
- Mixed with sawdust
- Offsite disposal in landfill
Marcellus Shale Gas Development

Multi-Stage High-Volume Hydraulic Fracturing of Horizontal Laterals

3,000 – 8,000 ft

4,000 ft
3 to 5 million gallons of water for hydraulic fracturing of each horizontal lateral
Typical Components of Frac Fluid

- For a 3 million gallon frac job, the 0.5 percent is equivalent to 15,000 gallons of “chemistry”

- Re-fracing may be needed due to proppant crushing, scale, etc.
Barnett Shale

Infill Drilling

- 500’ Apart
- 1,000’ Apart

Refrac

Well: Pittard #6H

Devonenergy.com
Water Withdrawals for Frac Water

- Surface-water withdrawals and municipal supply in PA
- Water-availability issues are seasonal in nature
- Withdrawal of 5 MGD during high water insignificant, during low water exceeds 10 percent of flow
- Cumulative impacts of multiple withdrawals
- If surface water becomes more restrictive, industry will look to groundwater
- Surface water and groundwater – a single resource
Water quality of flowback (1.5 million gallons) from Marcellus shale well after completion of hydraulic fracturing (Samples were taken at 1, 2, and 3 third intervals of the 2-week flowback period, PADEP)
TDS and Radioactivity of Flowback Water

![Graph showing the relationship between Total Dissolved Solids (TDS) and Gross Alpha Radiation in pCi/L. The x-axis represents Total Dissolved Solids (mg/L) ranging from 0 to 400,000, and the y-axis represents Gross Alpha Radiation in pCi/L ranging from 0 to 25,000. The data points are scattered, indicating a positive correlation between the two variables.]
**Uranium & Thorium to Radium & Radon**

**Radioactive Decay Series**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half Life</th>
<th>Count Rate (pCi/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium 238</td>
<td>$4.49 \times 10^9$ y</td>
<td></td>
</tr>
<tr>
<td>Protactinium</td>
<td>$1.18 \times 10^4$ y</td>
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<tr>
<td>Thorium 232</td>
<td>$1.41 \times 10^3$ y</td>
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<tr>
<td>Radium 226</td>
<td>1622 y</td>
<td>20,800</td>
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<tr>
<td>Radon 222</td>
<td>3.825 d</td>
<td>2,390</td>
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<tr>
<td>Uranium 234</td>
<td>0.5 pCi/L</td>
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</tr>
<tr>
<td>Thorium 232</td>
<td>0.0 pCi/L</td>
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<tr>
<td>Thorium 228</td>
<td>47.5 pCi/L</td>
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<tr>
<td>Radium 228</td>
<td>1,250 pCi/L</td>
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<tr>
<td>Radium 226</td>
<td>10,200 pCi/L</td>
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</tr>
<tr>
<td>Thorium 226</td>
<td>2,390 pCi/L</td>
<td></td>
</tr>
<tr>
<td>Uranium 238</td>
<td>20,800 pCi/L</td>
<td></td>
</tr>
</tbody>
</table>

**Brine from a Marcellus Shale-Gas Well**

Gross Alpha: 20,800 pCi/L  
Gross Beta: 2,390 pCi/L  
Radium 226: 10,200 pCi/L  
Radium 228: 1,250 pCi/L  
Thorium 228: 47.5 pCi/L  
Thorium 232: 0.0 pCi/L  
Uranium 234: 0.5 pCi/L
Municipal wastewater treatment plants not designed to handle flowback chemistry

Limited number of disposal wells in Ohio

Reuse flowback, onsite treatment for solids / blend with 70 % freshwater
Microseismic Monitoring of Hydraulic Fracturing
Marcellus Hydraulic Fracturing

• Produces readily detectable microseismic events (400 per frac)
• Frac half lengths greater than 1,000 feet
• Frac azimuths typically east-northeast parallel to J1 joint sets
• Reactivation of pre-existing joints by strike-slip failure

Duncan and Williams-Stroud (2009)

Microseismic for five Marcellus laterals

Joint sets in the Appalachian Basin
Stratigraphy and Frac Barriers

Modified from Kostelnick (2010)
Microseismic Monitoring of Marcellus Fracs

(Marcellus SPE 131783)
Microseismic Mapped Frac Tops and Bottoms
Marcellus Shale
Fracing near faults

Sharma and others (2003)
Seismic Line from South-Central New York

Tully
Marcellus
Onondaga
Salt
Lockport
Utica
Trenton

Smith (2010)
Avoid Structures
Valley-Fill Aquifers

Saturated deposits of glacial sand and gravel
Upper Devonian Fractured-Bedrock Aquifers

Fractured zone in Catskill Formation
Upper Devonian Fractured-Bedrock Aquifers

Bedding fracture and joint in Lock Haven Formation

Braun and others (2011)
Water Wells that Penetrated Saltwater in South-Central New York

Modified from Williams (2011)
Water Wells that Penetrated Saltwater in North-Central Pennsylvania

Williams and others (1998)
Water Quality of Typical Freshwater and Salty Water Wells in Upper Devonian Bedrock

Salty water wells (Williams and others, 1998)

Tioga County, PA
Depth of Freshwater Zones Penetrated by Gas Wells
South-Central New York
Wells that Penetrated Gas above the Marcellus Shale
South Central New York

Modified from Williams (2011)
Freshwater and Gas in Close Vertical Proximity
Methane in Water Wells
Marcellus/Utica Gas-Play Area

Sampling sites

Osborn and others (2011)
Good Zonal Isolation

- **Conductor Pipe**
- **Surface Casing**
- **Production Casing**

Layers:
- **Fresh Water Aquifer Zone**
- **Shallow Producing Zone**
- **Intermediate Producing Zone**
- **Target Producing Zone**
Poor Zonal Isolation

**PRESSURE BUILDS UP**

CONDUCTOR PIPE

SURFACE CASING

PRODUCTION CASING

FRESH WATER AQUIFER ZONE

SHALLOW PRODUCING ZONE

INTERMEDIATE PRODUCING ZONE

TARGET PRODUCING ZONE

CASING

CEMENT

FORMATION

SWN
Southwestern Energy*
Protection of Freshwater Aquifer

Characterization of deep freshwater and shallow gas and saltwater

Engineered zonal isolation by multiple casings, cement, packers, and venting
Geophysical Logs and Base of Freshwater Aquifer

Log data courtesy of Shell Appalachia
Shale Gas Development
Typical past practices

- Cemented surface casing may not be deep enough to protect freshwater aquifer

- Open annulus interval between top of production casing cement to bottom of surface casing may allow upward migration of salty water and gas

- Drilling and frac fluid storage in surface impoundments and burial of drill cuttings onsite may contaminant shallow groundwater and surface water

- One-time use of frac fluid wasteful of freshwater resources and creates disposal issue

- No water-well sampling before drilling/hydraulic fracturing operation
Shale Gas Development
Best practices based on state-of-the-art technology and science

• Geophysical logging to delineate base of freshwater aquifers

• Surface casing/cement deep enough to protect freshwater aquifers

• Intermediate and production casing/cement/packers to prevent upward migration of salty water and gas

• Cement-bond logging and pressure testing to ensure good seals

• Drilling and frac fluid storage in tanks and offsite burial of drill cuttings

• Avoid hydraulic fracturing near structures

• Microseismic monitoring of hydraulic fracs

• Reuse of frac fluid reduces freshwater resource impacts and disposal issue

• Water-well sampling before and after drilling/hydraulic fracturing operation
“ZEALOUS FOR THE MARCELLUS”