A Geological Analysis of the Appalachian Basin
and How It Affects the Oil & Gas Industry

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Executive Summary

The Appalachian Basin includes all or parts of ten states and some segments of Lakes Erie and Ontario comprising about 230,000 sq mi of the Eastern United States. It stretches more than 1,000 miles from the Canadian border to central Alabama. The oil & gas industry has been in the Appalachian Basin for over 150 years. The first intentional well was drilled by Colonel Edwin Drake in Titusville, PA during 1859. However, salt miners were the first Americans to drill for oil and natural gas. This area has the largest natural gas reserve in the United States and is all possible due to the unique geology of the Appalachian Basin.

Hundreds of millions of years ago, there were a series of orogenic events that resulted in this unique geology. The first was the Taconic Orogeny, where the oceanic Iapetus Plate collided with the continental North American Plate during the Ordovician Period and resulted in the deposition of the Utica Shale. The following tectonic event was the Acadian Orogeny, where during the Devonian Period, the Baltica Plate and Laurentia Plate collided. It was during this time that the Marcellus Shale was deposited. During a third orogeny, the Alleghanian Orogeny, the Utica and Marcellus Shales were naturally fractured when Gondwana and Laurentia collided during the Permian.

This orogenic activity has led to the area becoming greatly thrust-faulted, folded, and telescoped mainly at the close of the Paleozoic Era. The Valley and Ridge segment of the basin abuts the Appalachian Plateau segment on the east. To the east of the Valley and Ridge segment are the Blue Ridge and Piedmont segments. There is a major thrust-fault system under the eastern and central parts of the Appalachian Plateau. Within the petroleum industry, this area is known as the Eastern Overthrust Belt as an analog of its western counterpart in the western Cordillera Belt. Because of the Eastern Overthrust Belt’s structural traps and associated zones of fracture porosity, the Eastern Overthrust Belt is an important element of the Appalachian Basin.
Many oil and gas fields in the Appalachian Basin occur because zones of fracture porosity form the reservoirs.

In order for there to be an accumulation of hydrocarbons within the rocks, the environment needs to contain four things: source, seal, reservoir, and trap. If any of the four things are not present, there is very little chance that a supply of hydrocarbons will be present in that particular area. Hydrocarbons form when marine plants and animals die and decompose on the seafloor. They are then buried under many layers of sediment where the intense heat and pressure will convert them to hydrocarbons. The Appalachian Basin contains two sequences of dark-gray, dark-brown, and black marine shale, rich in organic matter. Those sequences are the Utica and Marcellus Shales. Shale is not only a source of hydrocarbons, but it can also be a seal. A seal needs to have low porosity and permeability, and shale perfectly matches these criteria. In unconventional reservoirs where the actual shale formation is the target, the formation itself acts as the seal, so it’s known as self-sealing. Since the Appalachian Basin is full of thrusting, folding, and faulting, there are many sources of possible traps. The two main reservoirs where the hydrocarbons accumulate are the Utica and Marcellus Shales.

The geology of the area provides everything needed for this area to economically produce hydrocarbons. However, it does pose several challenges that need to be taken into consideration. Topography can make the initial costs of hydrocarbon recovery somewhat high. The area tends to be very hilly, so large volumes of dirt or trees may need to be moved in order to provide a flat surface for the pad location. While the well is under flowback, the water tends to have high numbers of total dissolved solids which need to be taken care of before disposal or reuse. Also, geomechanics plays a huge role in fracture patterns and breakouts, which could cause stuck pipe, require hole cleaning, and can affect well logging and cement jobs.
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Introduction

In the heart of the Appalachian Basin lies what has become an epicenter for one of the fastest growing industries in the country. Home to the Marcellus, Utica, and Devonian Formations, areas such as Belmont and Washington counties in Ohio; Brooke, Ohio, and Marshall counties in West Virginia; and Washington (the energy capital of the East), Greene, and Allegheny counties in Pennsylvania have all experienced a tremendous increase in the amount of industry activity since the boom of 2010.

From 2011 to 2016, the Appalachian Basin produced 28 trillion cubic feet of natural gas and 102 million barrels of crude oil and condensate. By 2020, this area, which has the largest natural gas reserve in the United States, is expected to account for 35% of total US production. This basin has provided abundant fossil fuels for at least the last 150 years.

What characteristics of the area make this possible? The Appalachian Basin has a total area of about 230,000 square miles and contains more than 550,000 cubic miles of Paleozoic rock ranging in age from Early Cambrian to Early Permian. Within these rocks lay several major oil and gas plays that contain all the right components to be economically viable.

This area may provide several advantages for the industry, but any operation comes with some associated challenges. Some of those include topographical features that limit surface hole location, restricted road use for heavy equipment, and increased pad construction costs. Another element that needs to be taken into consideration is the naturally occurring radioactive minerals found in this area, which requires extra attention in environmental protection with water recycling and cuttings disposal. Also, the geomechanics within the area can display some unexpected side effects, which could be costly.
Industry Overview

When most people hear the words “American oil”, their thoughts immediately flicker to the Texas Panhandle, the Oklahoma Plains, or the Louisiana Gulf. But the fountainhead of the American petroleum industry is right in the roots of Appalachia. In the mid to late 19th century, the Appalachian Basin beckoned an influx of inventors, speculators, entrepreneurs, and wildcatters determined to make their fortunes.

Oil and natural gas were discovered in the Appalachian Basin long before they were ever commercially produced. Inadvertently, salt miners within Appalachia were the first Americans to drill for oil and natural gas. In 1814, a well in Noble County, Ohio being drilled for saltwater struck oil and in 1815 a well in Charleston, West Virginia struck gas. However, the first successful and best-known intentional oil well wasn’t discovered until August 27, 1859, in Titusville, Pennsylvania by Colonel Edwin Drake on behalf of the Seneca Oil Company (Figure 1). Other major wells were also drilled in Petroleum, West Virginia (1859); California, West Virginia (1860); Burning Springs, West Virginia (1860); and Washington County, Ohio (1860).
Geologic Overview

Geological History

In order to understand the time frame for the following events, a geologic time scale with dates is below in Figure 2.

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Figure 2: Geologic Timescale

During the middle Ordovician Period (440-480 mya), a change in Plate motions set the stage for the first Paleozoic mountain-building event in North America. This event is known as the Taconic Orogeny. During the Taconic Orogeny, the once quiet Appalachian passive margin changed into a very active plate boundary when the neighboring oceanic plate, Iapetus Plate, collided with the North American Plate and began to sink below it (Figure 3). The early stages of this uplift resulted in the deposition of black shale, which we know today as the Utica Shale.4
With the birth of this subduction zone, Laurentia formed and the early Appalachians were born. Along the continental margin, volcanoes grew coincident with the initiation of subduction. Thrust faulting uplifted and warped older sedimentary rocks laid down on the passive margin. As the mountains rose, weathering began to wear them down. Sediments from this erosion were carried downslope by streams to be deposited in nearby lowlands. By the time of the Early Silurian, the Taconic Mountains were lowered so much that less sediment arrived in the interior basin. With continued subsidence, shallow-marine conditions returned depositing primarily shale and limestone.\(^4\)

During the Devonian Period, the shallow interior seaway was disrupted by a major disturbance along the margin of Laurentia. This tectonic disturbance is known as the
Acadian Orogeny. While the proto-Atlantic continued to close and plates converged, the Baltica Plate collided with the northern part of the Laurentia Plate (Figure 4). With a high mountain system on its eastern border, Pennsylvania received enormous quantities of river and delta sediment, known as the Catskill Delta, for a long period of time. The Marcellus Shale was deposited in a relatively shallow sea about 380-390 million years ago during the initial stage of the Acadian Orogeny.4

Figure 4: Acadian Orogeny Visual

About 270 million years ago during the Permian, Gondwana and Laurentia collided resulting in a third mountain-building event known as the Alleghanian Orogeny (Figure 5). The compressive stress that accompanied this collision was so intense that large portions of the Laurentian crust and overlying sedimentary sequence were thrust westward toward the continental interior. Above the thrust planes, the sedimentary strata which had been deposited over hundreds of millions of years were warped and folded as they were forced west. It was during this time that the Marcellus and Utica Formations were naturally fractured.4
The breakup of Pangea began in the Late Triassic Period in the Early Mesozoic Era. As it began to drift apart, a new passive tectonic margin was created and the forces that created the Appalachian Mountains were ceased. Weathering and erosion set-in and the mountains began to wear away. They were eventually eroded to an almost flat plain by the end of the Mesozoic Era. The distinct topography of the present wasn’t formed until the region was uplifted during the Cenozoic Era.  

**Structural**

The Appalachian Basin includes all or parts of ten states and some segments of Lakes Erie and Ontario comprising about 230,000 sq mi of the Eastern United States. It stretches more than 1,000 miles from the Canadian border to central Alabama. The width of the basin varies from 75 to 350 miles; larger being near the border and decreasing south. The Appalachian Plateau, its most extensive subdivision, covers about 135,000 sq mi from the Canadian border to central Alabama where it melds with the Black Warrior Basin to the west and southwest. The Valley and Ridge segment of the basin abuts the Appalachian Plateau segment on the east and
covers an area of about 45,000 sq mi from New York to central Alabama. To the east of the Valley and Ridge segment are the Blue Ridge and Piedmont segments (Figure 6). 

Figure 6: Physiographic Map of the Appalachian Highlands
Cross-sectional views reveal that the Appalachian Basin is asymmetrical with the rocks on the west flank dipping eastward. The dips range from about 2,000 to 5,000 feet below sea level increasing eastward to more than 50,000 feet below sea level. The Appalachian Plateau segment is generally composed of gently dipping strata. The Valley and Ridge segment, however, has been greatly thrust-faulted, folded, and telescoped by orogenic events that occurred mainly at the close of the Paleozoic Era during the Alleghanian Orogeny. The metamorphic rocks composing the Blue Ridge and Piedmont segments were thrust more than 150 miles westward over a wedge of Paleozoic Valley and Ridge sedimentary rocks. As a result of the thrusting, the easternmost segment of the Appalachian Basin is hidden beneath the Blue Ridge and Piedmont province. The extent of the eastern hidden segment of the basin is not well defined and known only from a few deep reflection seismic profiles and a scattering of fensters in the Blue Ridge of eastern Tennessee and adjacent North Carolina.5

Thrust faulting and associated folds which are produced by duplication of parts of the stratigraphic sequence are not restricted to the Valley and Ridge segment or the eastern buried segments of the Appalachian Basin. There is a major thrust-fault system under the eastern and central parts of the Appalachian Plateau. Décollements follow several zones of shale and evaporitic rocks in the Cambrian to Devonian sequence. Anticlines commonly formed where thrust faults ramped steeply across sequences of resistant, more brittle beds between décollement levels where thrusts splayed into thick sequences of middle to upper Paleozoic clastic strata. Within the petroleum industry, this area is known as the Eastern Overthrust Belt as an analog of its western continent counterpart in the western Cordilleran Mobile Belt. The Eastern Overthrust Belt’s western boundary is the western limit of Alleghanian thrusting. The western boundary of the Eastern Overthrust Belt is completely in the subsurface because bordering thrust faults do not crop out. The western boundary of the overthrust belt is sharply defined at places such as the
Burning Springs anticline in northern West Virginia and along the Bass Islands trend of Chautauqua County in western New York. At most other places, the terminal faults are not easily located and the west edge of the belt is not as clearly delineated.5

Because of the belt’s structural traps and associated zones of fracture porosity, the Eastern Overthrust belt is an important element of the Appalachian Basin. Many oil and gas fields in the Appalachian Basin occur because zones of fracture porosity form the reservoirs. Gas fields in the Oriskany Sandstone are good examples of anticlinal fault traps in which fractures are the dominant type of porosity.5

Figure 7: Appalachian Basin Bedrock Geology
**Oil and Gas Capabilities**

Hydrocarbons form when marine plants and animals die and decompose on the seafloor. There is insufficient oxygen on the seafloor, so they do not decompose entirely. The remains mainly consist of carbon and hydrogen. The partially decomposed remains will eventually become covered by multiple layers of sand, silt, and mud. As the depth of the sediment burial reaches about 10,000 feet, the natural heat of the earth and the intense pressure will act upon the sediments and over time form hydrocarbons. In order for there to be an accumulation of hydrocarbons within the rocks, the environment needs to contain four things: source, seal, reservoir, and trap. If any of the four things are not present, there is very little chance that you will find a supply of hydrocarbons in that particular area.

**Source**

A source rock contains organic-rich sediments that will expel hydrocarbons after being heated during burial. The sedimentary organic materials within the rock are known as kerogens. Kerogens are partially transformed into hydrocarbons when heated. The most prominent source rocks are ocean deposited, organic-rich black shales. They contain a mixture of marine microorganisms and terrestrial particulate organic matter. Because of this, black shales generally yield a mixture of gaseous and liquid hydrocarbons. Another prominent source rock is coal. Coal is the product of woody organic matter accumulating in swamp environments and tends to only yield methane during maturation. Oil shales are lake shales that contain large amounts of kerogen. They tend to yield the most oil-rich hydrocarbons but are not as widespread as marine shales. Any sedimentary rock such as limestones, siltstones, sandstones, etc. can be a source rock. It just has to contain organic matter.

The Appalachian Basin contains two sequences of dark-gray, dark-brown, and black marine shale, rich in organic matter. These sequences have been documented as major source
beds of oil and gas. The younger sequence, ranging in age from Middle Devonian to Early Mississippian, is extensive beneath the Appalachian Plateaus from New York to Alabama. The Devonian shale source-bed sequence includes many black shales from the Lower Devonian Mandata Formation to the Lower Mississippian Sunbury Shale. Adjacent to its pinch out in southern Tennessee, the Devonian source-bed sequence consists of one or two beds of black shale in about 30 ft of the Upper Devonian Chattanooga Shale. Throughout New York, Pennsylvania, and West Virginia, the shale sequence is lighter gray, siliciclastic, and coarser grained so it is more porous. These provide reservoirs for the oil and gas derived from the black Devonian source rock. There is an older source bed that is Middle to Late Ordovician in age. It consists mostly of brownish to black marine shale with small amounts of gray shale, siltstone, or intercalated nodular argillaceous limestone. The sequence is known as the Utica facies and includes the Athens Shale in Alabama, the Blockhouse Shale in Tennessee, the Paperville Shale in southwestern Virginia, the Antes Shale in Pennsylvania, the Utica Shale in northern Ohio, and the Point Pleasant Formation in southwestern Ohio.5

Other marine shales that may have some potential as source beds include the Middle and Upper Cambrian Conasauga Group, the Middle Ordovician Wells Creek Formation, the Lower Silurian Cabot Head Shale, the Middle Silurian Rochester Shale, and the Lower Devonian Mandata Shale. Possible source beds in Mississippian and Pennsylvanian rocks include the many coal beds and associated canneloid shales in the Appalachian Plateaus, the Lower Mississippian coals of Virginia’s Valley coal fields, and the anthracite of the eastern Pennsylvania anthracite fields.5
**Thermal Maturation**

Thermal maturity is the extent of heat-driven reactions that alter the composition of organic matter (e.g., conversion of sedimentary organic matter to petroleum or cracking of oil to gas). The degree of thermal maturation of source rocks depends largely upon the thickness of sediment, depth of burial, and existing thermal gradient. The basin’s Paleozoic sequence thickens from west to east due to a nearly continuous deposition in the central and eastern parts of the basin. Because of this, the thermal maturity of the basin also increases from west to east. As the source rock matures, it goes from producing oil (blue on **Figure 8**) to wet gas to dry gas to being overmatured and producing nothing (deep red on **Figure 8**).

**Figure 8:** Thermal Maturation Determining Oil, Gas, or Condensate
**Seal**

A seal, also known as a cap rock, is an impermeable layer that oil and gas cannot pass through effectively. The seal is what holds the hydrocarbons within the geometry of the trap. Shale is the most important and most common seal rock. Shale can also be just as effective if it is in thin layers within a formation of other rock types. Evaporite rocks such as gypsum and halite are also capable of being seals and can occur as a continuous layer across a basin. Any rock can be a seal depending on their porosity and permeability characteristics. Conventional reservoirs require a separate seal from the source rock, but in unconventional reservoirs, the source acts as a seal.

**Trap**

A trap is a three-dimensional geometry within the rocks that allows the hydrocarbons to accumulate. There are two types of conventional traps shown in Figure 9. The first is structural traps. In structural traps, the sedimentary layers have been deformed to form a shape within which hydrocarbons can accumulate. They include anticlines, fault traps, and traps around salt domes. The second type of conventional trap is stratigraphic traps. They form when the deposition of sediments results in an isolated reservoir surrounded by impermeable sediments. Examples include a reef or sand-filled river channel surrounded by shale or evaporites. The folding and faulting present within the Appalachian Basin provides many potential traps.
Reservoir

A reservoir is a porous and permeable rock in which hydrocarbons accumulate. There are two main types of reservoirs that may be seen. The first is a conventional reservoir. They include rocks like sandstone and limestone that contain spaces within and between the grains. The types of pores within conventional reservoirs include intergranular (the spaces between the grains), intragranular (the spaces within the grains), fractures, molds (shaped like dissolved fossils or minerals), and vugs (irregularly shaped voids formed by dissolution). The second type of reservoirs are unconventional reservoirs, which lack adequate porosity and permeability to permit the flow of hydrocarbons. Drilling this type of reservoir wouldn’t have even been considered only a decade or two ago, but they make up many of the most important trends in hydrocarbon industry plays today (Figure 10).
Figure 10: Basin and Shale Play Map for the United States
Industry Challenges

**Pad/Lease Road Construction and Location**

The average pad size is between 4 and 25 acres depending on how many wells it will contain. The average number of wells per pad is about ten, but super pads containing up to 40 wells are becoming more present. Pads containing more wells will need more space. A lot of land in this area is covered in trees. Trees will need to be removed to allow space for the pad and lease road. Also, the area tends to be very hilly, so in order to create a flat surface for the equipment a lot of land may need to be moved. The more that needs to be moved, the higher the cost.

Not only does there have to be enough space for the wells, but for the vast amount of equipment that will be on the pad during its different stages (Figure 11 & 12). Most likely, the largest equipment on pad will be the drilling rig and the frac fleet. There needs to be adequate room for these essentials, but also extra room for people and other vehicles to safely move around.

*Figure 11: Example Drilling Pad*
In order to minimize pad size, several things can be done. The main thing that should be done is only have necessary equipment/amenities on pad at a certain time. Another would be to limit the size, amount, and shape of the equipment/amenities. For example, if water cannot be transferred to pad from another location, it needs to be stored on site either in an impoundment or an AST. Typical AST’s are round which could cause them to take up a lot of room. Instead of a round AST, a stadium AST can be used. Also, developers can try to find pad spaces in areas that are relatively flat and need little vegetation or dirt moved.

Throughout a pad’s life, it will be frequented by many large and heavy pieces of equipment. This equipment needs to have a way to safely and easily make it to the pad. The community roads in the area need to be able to handle the increase in traffic and weight it will see during this time. Many roads have weight, height, width, and/or length restrictions. If any of the equipment exceeds these, the road may not be able to be used and the pad may not be accessible. While designing the pad, it needs to be certain that there is enough space for a lease road to be put in if there is not already a road leading to location. These amenities will be permanent during the longevity of the well so they are very important. It is very easy for costs to accumulate during this stage.

**Figure 12:** Example Frac Pad
Water Supply and Brine/Cuttings Disposal

Water plays a large role in the oil & gas industry. It is present when drilling the well (drilling fluid or mud used to lubricate and cool the bit, provide hydrostatic pressure to offset the formation pressure, and carry cuttings to the surface), preparing a well for production (hydraulic fracturing and collecting flowback water), and producing the well (collecting, treating, and disposing of fluids).

The largest need for water is during hydraulic fracturing, which uses about 4-6 million gallons per well. During a high production year in the Marcellus, it is estimated that 80 million gallons of water are required per day. Sources for this amount of water include local ponds or streams, constructed reservoirs, the public water supply (used municipal water or groundwater), and wastewater from other wells.\(^7\)

Wastewater management is complicated by the rapid changes in water quantity and water quality over time. The volume of flowback water declines sharply after the first few hours to days while concentrations of total dissolved solids and other constituents in flowback and produced water increase rapidly. The following figure, **Figure 13**, shows two graphs that were made from flowback data. Graph A shows total radium activity and total dissolved solids related to time since initiation of flowback for a well in Washington County, Pa. The data shows that the amount of total dissolved solids in the flowback water increased rapidly within the first few days and then steadily increased for the remaining time. Graph B shows the total radium activity and Ra-228/Ra-226 related to time since initiation of flowback for a well in Greene County, Pa. The data shows that the total amount of radium in the flowback water greatly increased after the initiation of flowback.
Figure 13: Flowback Water Quality Versus Time
In states such as Pennsylvania, flowback and produced water is being reused in large amounts. This mostly accounts to the fact that options for injection wells are limited; the number of wells being drilled in the future will decline while all the already drilled wells will continue to produce water. More water being produced than can be recycled will require additional water management facilities needed in the region. This is something the industry should look at closely to ensure they will be able to properly dispose of this water in the future.

The most common way to manage wastewater is to inject it into a disposal well. Other management techniques include removing metals and other contaminants to create clean brine, desalinizing clean brine to create clean freshwater, evaporating the water to dryness or crystalline form, and filtering flowback water to remove suspended solids and blending it with freshwater for use in a subsequent fracturing job. Since only 10-20% of the volume of fracture fluid returns to the surface, 80-90% freshwater must be added to the flowback water for recycling. Such a small fraction of water is returned because the fracturing process creates a significant surface area which attracts moisture. The shale actually imbibes most of the water.7

The water quality issues that are primarily related to the industry in the Appalachian Basin are high concentrations of total dissolved solids in the produced water, the migration of stray gas into the water supply, and the potential migration of water from deep formations into shallow aquifers. The Marcellus Shale typically produces water with 180,000 milligrams per liter dissolved solids after a few weeks of production. Before the water can be reused, it needs to be substantially adjusted to avoid degrading well performance.

Produced water may also contain certain problematic constituents. An example would be barium. Barium can combine with the sulfate in water used for recycling, which could cause sediment to build up in the wells. The drill cuttings can also contain hazards such as uranium and radium, which could mobilize under acidic conditions. Uranium tends to stick to particles, so the
uranium content of produced water is low even if the uranium content of organic-rich black shale is high. Although water produced from the Marcellus is low in uranium, the concentrations of radium and strontium tend to be high and increase over time. Bromine is also found in high concentrations and can react with organic compounds in surface water to produce trihalomethanes. Trihalomethanes are the four chemicals chloroform, bromodichloromethane, dibromochloromethane, and bromoform. Exposure to these chemicals have been linked to increases in certain cancers and heart, lung, kidney, liver, and central nervous system damage.⁷

Combustible gasses such as methane are also common occurrences. Sources are believed to be naturally occurring gas seeps; abandoned or operating gas wells, coal mines, or landfills; coalbed methane wells; natural gas storage fields and pipelines; shallow formations and aquifers; buried organic matter; and drift gas deposits. The geologic variability and the legacy of coal and mineral mining, oil and gas production, and other industrial activities greatly complicate water quality studies within the Appalachian Basin.⁷

**Geomechanics**

The earth’s crust is constantly subjected to forces that push, pull, or twist it. These forces are called stress. In response to stress, the rocks undergo deformation known as strain. Geomechanics encompasses how stresses and strains within the earth affect what we drill into and explore for. The magnitude and direction of stresses and how they affect the rock properties in a region, a field, and a wellbore have a massive impact and control on what we do in unconventional exploration and exploitation.

Stress is a force per unit area, and if we visualize a point within the earth as a cube it can be visualized as shown in **Figure 14**. The point is subjected to three normal stresses and six shear stresses. A simple rotation can be applied which results in the shear stresses going to zero leaving only the principal stresses shown in **Figure 15**. This assumes that the overburden is
vertical and horizontal stresses are normal to the vertical stress. This assumption holds true in most areas, except near large geologic structures such as faults, salt domes, and igneous intrusions where more complicated stress models are needed to describe the stresses within the earth.  

Figure 14

Within the earth, a formation's strength and the fluid it contains dictates how stresses act and distributes within the formation. As a result, the pore pressure and rock properties of each formation need to be calculated or estimated to gain a full understanding of how stress acts within the earth. The pore pressure within a formation can help support the load that it maintains, and this needs to be taken into account when we estimate stresses.  

Figure 15

Before we drill a well, the formation is in a state of stress equilibrium. Drilling of the wellbore disrupts that equilibrium and causes stress to redistribute around it. We have mud weight to balance this dis-equilibrium, but commonly this is not enough to stop breakout or wellbore instability completely. By looking at the damage we cause in the borehole while drilling (via drilling, tripping in or out, surging and swabbing, etc.) we can estimate the stress directions in the formations we drill through and start to constrain the magnitudes of stresses with other drilling and completion data from the area. Breakouts occur in the direction of minimum horizontal stress, as the maximum compression (where breakout occurs) in the
wellbore happens 90 degrees from the maximum horizontal stress (in most cases). Because of this relationship, we can estimate $\sigma_H$, the maximum horizontal stress direction.\(^8\)

It is possible to make estimates of stress magnitudes once the direction of stresses is known. Overburden, $\sigma_v$, can be calculated using information from density logs. Integrating the density of the overlying rock and multiplying by the acceleration due to gravity will give the overburden stress. The minimum horizontal stress, $\sigma_h$, can be estimated using leak off tests, offset completion data, or mini fracture tests within the wellbore. The hardest of the stresses to estimate magnitude for is the maximum horizontal. This is because there is no direct way to measure it, but it can be constrained either by using advanced sonic measurements or by using the severity of wellbore breakouts. The magnitudes of the horizontal stresses are of the utmost importance as the magnitudes with depth define the type of faulting regime, **Figure 16**, that the formation of interest lies in.\(^8\)

![Faulting Regimes](image)

**Figure 16**: Faulting Regimes
Almost all horizontal wells completed in unconventional resource development are drilled in the direction of minimum horizontal stress. This is done to contact and prop open the largest amount of reservoir by making fractures perpendicular to the horizontal well since the maximum horizontal stress direction controls the direction of stimulation propagation. As seen in Figure 17, the Appalachian Basin is almost all strike-slip or thrust faults with high horizontal stress ratios. High horizontal stress anisotropy does not allow the growth of induced complex fracture networks that permit maximum reservoir contact (Figure 18). Instead, planar fractures form (Figure 19).
Ratios of stresses also control how the wellbore breaks out in both the vertical and horizontal sections of the well. In most cases, people visualize breakouts occurring in a horizontal well on the sides of the well due to the overburden stress (Figure 20). In highly compressive environments like strike-slip or thrust fault regimes where at least one of the horizontal stresses is greater than the vertical stress, the breakout actually occurs at the top and bottom of the wellbore (Figure 21) instead of the sides. The Appalachian Basin fits into this category and may experience operational issues from stuck pipe, hole cleaning, well logging, and cement jobs.8

Figure 20
Conclusion

The unique geology of the Appalachian Basin is what makes it possible for the industry to be so prosperous in this area. If one feature had even the slightest change, everything could be completely different. Aspects such as water quality and geomechanics still pose operational complexities. However, the industry continues to evolve every day and make advances in technology that will allow for safer, more efficient, and higher recoverability practices.
Literary References


Figure References


F6. Hunt, 1967


F8. Taken from class lecture powerpoint


