Constraints on Marcellus Shale Gas Production, Northeast Pennsylvania, USA

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Section Sciences de la Terre de
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CONSTRAINTS ON MARCELLUS SHALE GAS PRODUCTION, NORTHEAST PENNSYLVANIA, USA

Thèse

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par

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Thèse de Monsieur Samuel Woolsey CARMALT

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«Constraints On Marcellus Shale Gas Production, Northeast Pennsylvania, USA»

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CONSTRAINTS ON MARCELLUS SHALE GAS PRODUCTION, NORTHEAST PENNSYLVANIA, USA

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Abstract

The Marcellus Formation in the Northeast United States has been known for centuries for being rich in hydrocarbons. But it is a mudstone, with the result that it has very low permeability. The advent of fracking at the beginning of the 21st century raised the possibility that this extensive hydrocarbon resource could be exploited. It has been, but the fracking technology still results in rapid decline curves with significant gas being left in place; hence the initial economic promise is only partially achieved. The details of geology are much less important for this type of play than for traditional oil and gas operations; more important are the economic parameters, specifically the hydrocarbon price and the political environment. Significant production of gas from northeast Pennsylvania using fracking technology started in 2009; calculations of production to date indicate that approximately 50% of the exploitable gas has already been produced given current technology and economic framework, meaning that by 2040 this resource will no longer be a significant energy source for the US economy.

Resumé

La Formation de Marcellus, au nord-est des États-Unis, est connue depuis des siècles pour sa richesse en hydrocarbures. Mais il s'agit d'un mudstone, ce qui lui confère une très faible perméabilité. L'avènement de la fracturation hydraulique au début du 21e siècle a soulevé la possibilité d'exploiter cette vaste ressource en hydrocarbures. Cela a été le cas, mais la technologie de fracturation hydraulique entraîne toujours des courbes de déclin rapide avec une quantité importante de gaz laissée en place ; la promesse économique initiale n'est donc que partiellement réalisée. Les détails géologiques sont beaucoup moins importants pour ce type de zone que pour les opérations pétrolières et gazières traditionnelles ; les paramètres économiques, notamment le prix des hydrocarbures et l'environnement politique, sont plus importants. Une production importante de gaz dans le nord-est de la Pennsylvanie grâce à la technologie de fracturation hydraulique a débuté en 2009 ; Les calculs de production indiquent jusqu'à présent qu'environ 50 % du gaz exploitable a déjà été produit, ce qui signifie que d'ici 2040, ce gaz ne constituera plus une source d'énergie significative pour l'économie américaine.

Chapter 1 -- Introduction

Despite what many people think, the economy runs on energy rather than on money (Soddy, 1926; Georgescu-Roegen, 1971, Zencey, 2009, Hall and Klitgaard, 2012; Stern, 2018; White and Hagens, 2019). This is observed in the correlation between energy and GDP, which is used as an indication of economic activity (figure 1-1).

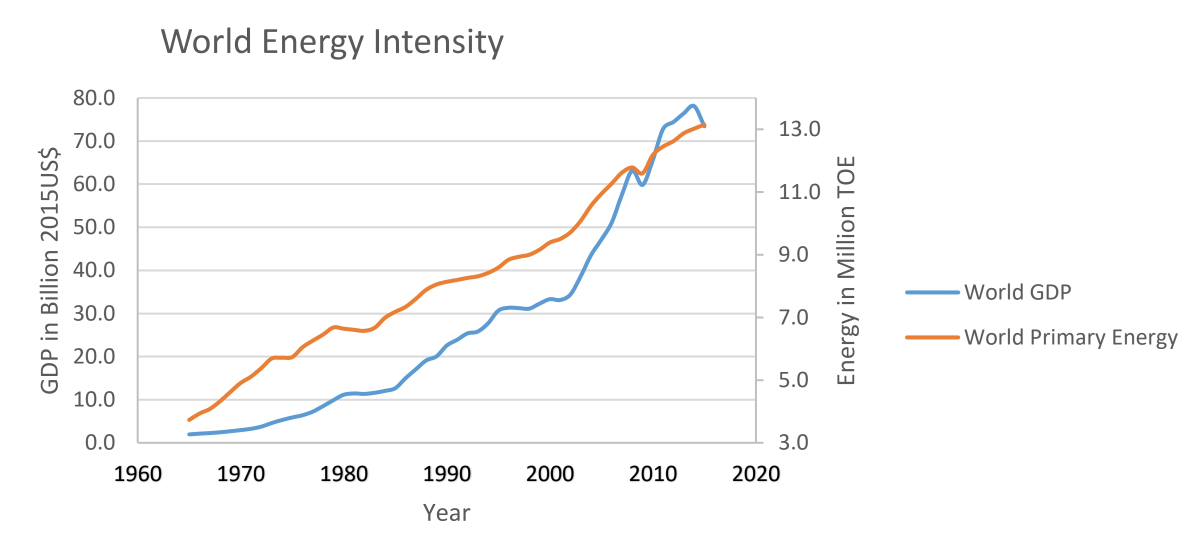


Figure 1-1 -- World energy intensity (data sources: World Bank, 2016, and BP Statistics, 2016)

The importance of energy as at least a factor in economic well-being has been recognized for centuries, with the result that there have been periodic episodes of worry about 'running out' of energy. Since the patenting of the improved seam engine in 1776, human societies have increasingly harnessed fossil solar energy by mining fossil fuels. This has led to successive concerns about running out of coal (Jevons, 1865), and then oil (USGS, 1922; Hubbert, 1956; Campbell and Laherrere, 1998; Deffeyes, 2001, 2005). When the financial bubble leading to the 2008 economic crash resulted in particularly high energy prices there was much concern that this time society really was running out of oil (Deffeyes, 2005; Mearns, 2008). Resources of natural gas, which geologically is closely associated with oil, became a major part of the discussion with the geologic question becoming how far into the future would natural gas be able to provide society's energy.

In the years leading up to 2008, a Texas company, Mitchell Energy, combined existing oil and gas drilling technologies to allow economic hydrocarbon exploitation from shales (Gold, 2014). The combined technologies, called 'fracking'[1], held promise for avoiding energy supply problems. Traditionally, oil (and gas) exploration and production relied on geologic time to concentrate hydrocarbons into fields, known in the industry as 'conventional' deposits. The fracking technology allows production from the original, usually fine-grained rocks, in which the organic matter was deposited; these are 'unconventional' or 'continuous' deposits. The potential to use the fracking technology to exploit hydrocarbons directly from the Appalachian black shales was one example of the optimism about the natural gas resource available in an unconventional deposit. In particular, the US government extensively researched the energy potential of the Appalachian black shales after the Arab oil embargo in the 1970s (see figure 1-2).

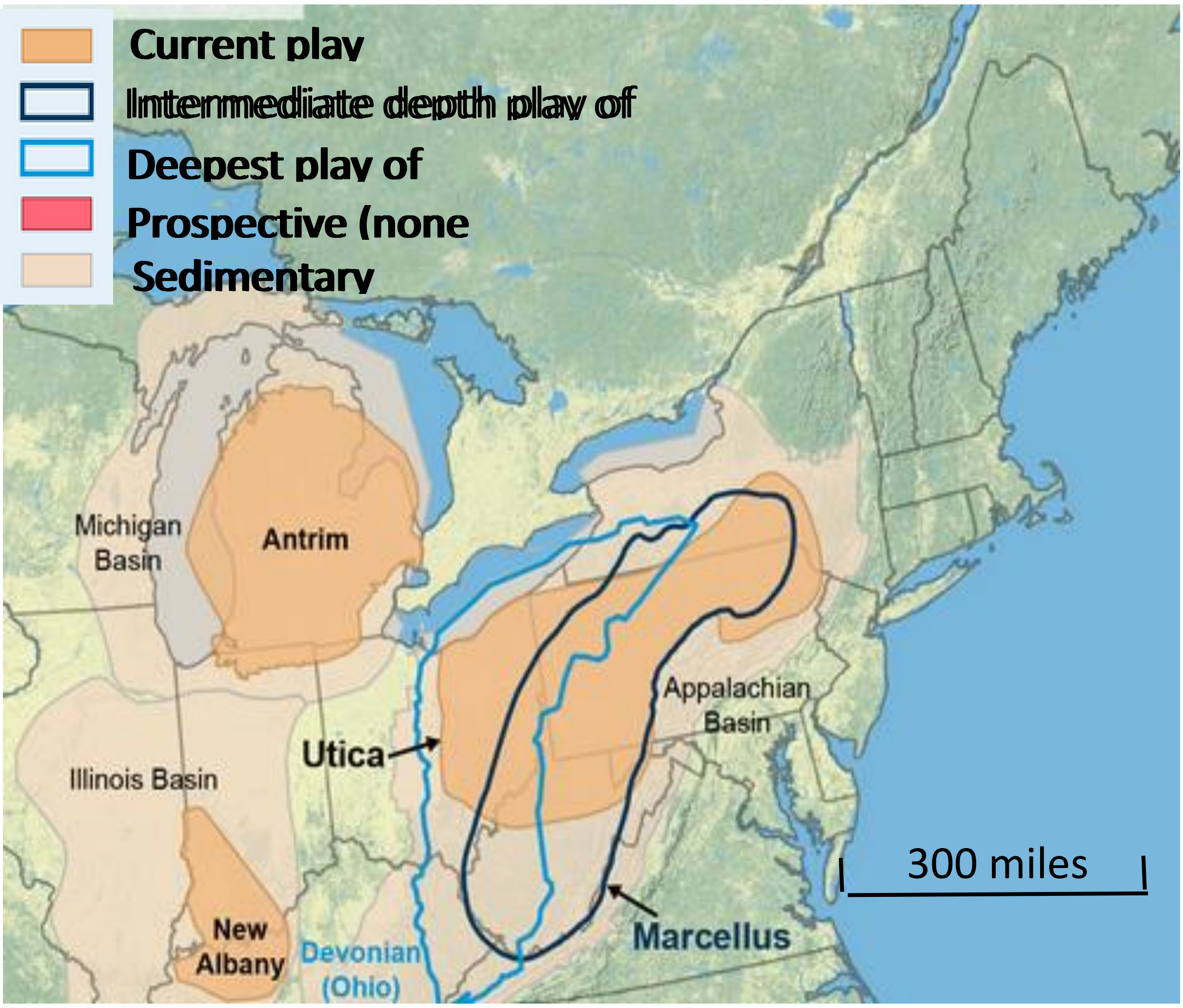


Figure 1-2 -- Location of the Appalachian Basin with principal black shales (EIA, 2016)

[1] The oil and gas industry prefers the term 'hydraulic fracturing', which is the technical operation. The term 'fracking' may just be a short version, but frequently is used to encompass the entire scope of activities, including such issues as site preparation, water use, etc., in addition to the hydraulic fracturing itself.

These investigations of the Appalachian black shales, made under the umbrella of the Eastern Gas Shales Project, significantly enhanced the understanding of the geology of the black shales. Nevertheless, in its final reports (e.g., Milici and Swezey, 2006) the potential of the resource from fracking was largely omitted despite the new fracking technologies just becoming available.

In early 2008, Pennsylvania State University geologist Prof. Terry Engelder published an estimate that did rely on these technologies. He and his colleagues estimated that the Marcellus Formation, the most extensive hydrocarbon-rich of the Appalachian black shales, had potential reserves of over 50 TCF (trillion cubic feet)[2] of natural gas (Engelder and Lash, 2008a, 2008b). Given the fact that the Marcellus shale underlies at least two-thirds Pennsylvania, and is also present in significant portions of New York, Ohio, and West Virginia the immediate reaction was that the Marcellus would provide energy in the form of natural gas for decades.

[2] Some press reports at the time cited 500 TCF, but in the article the authors are clear that that is the estimate of the total resource, with only an estimated 10% or 50 TCF being the amount they considered economically recoverable and hence reserves.

Figure 1-3 -- General area of the Marcellus "play" with circles indicating the most productive areas in northeast and southwest Pennsylvania.

Because of its proximity to major markets along the US East Coast, there was an immediate rush by companies to exploit the Marcellus shale gas resource. It soon became clear that the most economically productive areas in Pennsylvania were in the southwest and northeast of the commonwealth[3] (see figure 1-3), with the intervening areas less productive and therefore less profitable.

Unlike conventional oil and gas deposits, in which the hydrocarbons have been concentrated over geologic time by migration into permeable formations where they are trapped by impermeable barriers, the shale formations are themselves impermeable and preservation of the hydrocarbons is due to the properties of the rock itself. As such, the concept of 'field' does not really apply and unlike the traditional oil or gas field there are no sharp boundaries. In a 2017 paper Carmalt and Moscariello discussed the definitional issues with the concept of discrete oil and gas fields compared with continuous deposits such as the Marcellus; see Appendix A.

The goal of this research was to understand the factors, primarily geologic and economic, that were causing some areas of Pennsylvania to be more productive of natural gas from the

[3] Pennsylvania is one of the four United States that are technically a commonwealth rather than a state.

Marcellus Formation, and thus economically interesting, than others. While the underlying geology of the Marcellus shale was well documented, its potential for economic exploitation in light of the new fracking technology was not. This research was undertaken to investigate the issues that make some areas of the Marcellus Shale attractive to industry, and some not. In particular, the initial aim was to find geologic reasons for the differences; as the study progressed, two suggested limits to Marcellus exploitation were specifically checked: the role of the Appalachian Front and the role of internal decollements. It became increasingly clear that for the most part the economic structure of the industry is a major factor in understanding these questions.

Chapter 2 -- The geological setting and hydrocarbon history of the Marcellus Shale

Geologic and Tectonic Setting

The Appalachian Mountains define the eastern portion of the United States. They run southwest to northeast[4] from Alabama to Maine in the United States.

Figure 2-1 -- Appalachian Mountains (source:https://ch.pinterest.com/pin/96475616994052311/)

Geologically the orogenic belt can be traced even further to both the northeast and southwest. The geology of the Appalachians has been studied for over 200 years, with the result that there is a wealth of published literature; see, for example, Hall (1839), Rodgers (1949), Rodgers (1967), Rodgers (1970), Ettensohn (1985), Sloss (1988), Hatcher et al (1989), Faill (1997a, 1997b, 1998), and Hatcher (2010).

The Appalachians Mountains and associated Appalachian sedimentary basins form the type locality for the Wilson cycle of continental accretion (Wilson, 1966, 1968). The core of the North American craton, Laurentia, has been dated at 4.0 Ga (Iizuka et al., 2007). Over the subsequent 3 billion years, to at least 1.0 Ga, there were additions to the craton with the

[4] Unless otherwise stated, geographic directions are those of the present-day.

Grenville orogenies of 0.9 to 1.3 Ga forming the bedrock of Canada and the northeastern United States (see figure 2-2). These later Proterozoic rocks are also known from basement outcrops, boreholes, and inferred from geophysics throughout the Appalachian region (McLelland et al., 2010). Named by Logan (1863) for specific metamorphic strata about 1/3 of the way from Montréal to Ottawa, the term 'Grenville' has been used for virtually all pre-Cambrian basement rocks of later Proterozoic age throughout the United States. The metamorphosed Grenville rocks form the cratonic basement for all of the subsequent Appalachian sedimentation.

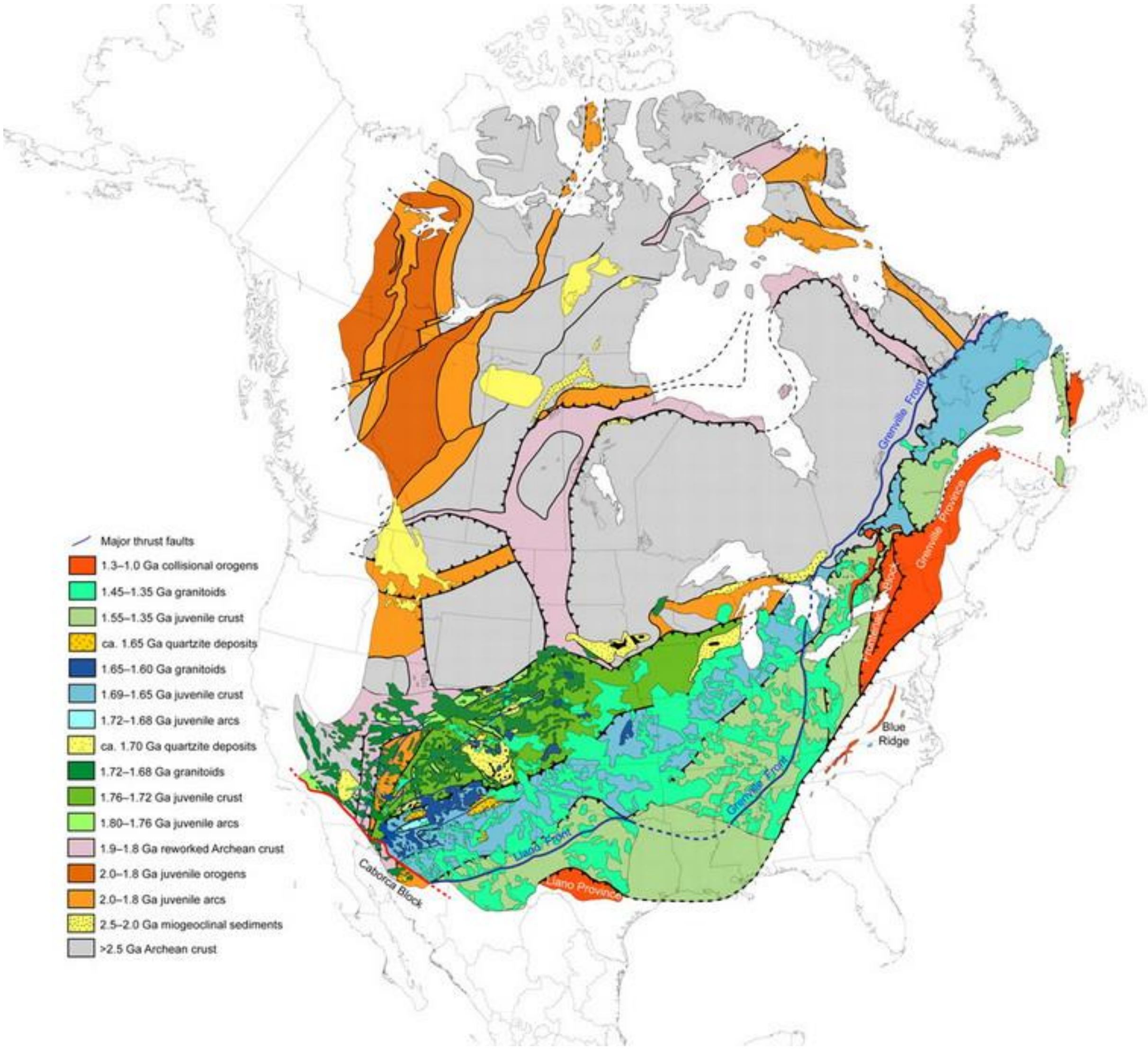


Figure 2-2 – pre-Cambrian accretion of the Laurentian shield (after Whitmeyer and Kalrstrom, 2007).

The Appalachian mountains were built during the Paleozoic along the eastern and southeastern margin of the shield by three major orogenic episodes: the Taconic, Acadian and Alleghenian (Hatcher, 2010; Murphy et al., 2010; Nance et al, 2011). In the later pre-

Cambrian, the area was a passive continental margin with the Iapetus Ocean to the southeast (Cawood et al, 2001; Domeier, 2016). Towards the end of the Ordovician the closing of the Iapetus Ocean is reflected in the Taconic orogeny. The Taconic orogeny was the result of collision with the Baltic shield in the northern Appalachians; it is less well known in the southern Appalachians where it is only seen in the subsurface (Rodgers, 1971; Mac Niocailli et al, 1997).

The Iapetus Ocean to the southeast of the Laurentian craton mostly disappeared with the Taconic collision as oceanic crust was subducted (Domeier, 2016). Further to the east and southeast, fragments of Gondwana rifted apart from that craton. Together with volcanics associated with the subduction, this provided sediments moving from east to west and northwest which were deposited on continental crust, leaving an expanding Rheic Ocean yet further to the east and southeast between the Laurentian craton and Gondwana (Mac Niocailli et al, 1997; Murphy et al, 2010; Pollock et al., 2012).

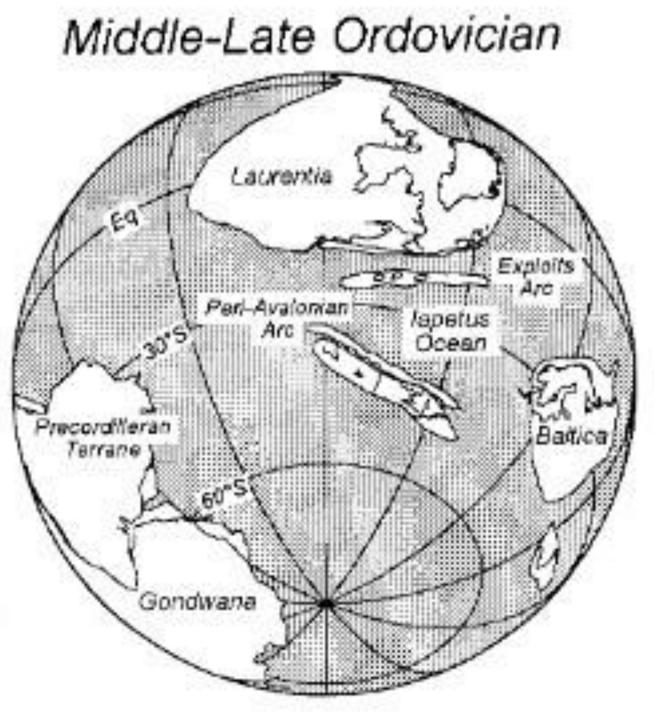


Figure 2-3 -- Closing of the Iapetus Ocean (after Mac Niocailli et al., 1997)

Then, from the middle Devonian to early Carboniferous, these eastern sediment sources collided with the augmented Laurentian craton in the Acadian orogeny (Faill, 1985; Ettensohn, 1992; Ettensohn, 2008, Wookcock, 2012). After the Arcadian orogeny the area was quiescent for most of the Carboniferous. During this time the extensive Appalachian coal beds were deposited (Hosterman et al., 1983; Rodgers, 1988; Klein, 1993; Chesnut, 1994). This was followed during the Permian by the collision of Laurentia with Gondwana (Slingerland and Furlong, 1989) to form Pangea. This Appalachian orogeny created high mountains; while high mountains no longer exist, much can be inferred from back-calculations of the resulting sediments deposited during the Mezozoic and Cenozoic. These sediments exist both to the east and southeast and also to the west northwest where they were eroded by the eastern half of the Mississippi River drainage system (Poag and Sevon, 1989, amongst others). The present Atlantic Ocean opened beginning in the later Triassic, and continues to widen today (Burke, 1976; Faill, 1997).

Geology and Stratigraphy

The Appalachian Mountain geology can be divided into distinct physiographic provinces (see figure 2-4). From northwest to southeast there is the Appalachian or Cumberland Plateau, characterized by relatively flat-lying strata. Next to the east is the Valley and Ridge Province, characterized by thrust faults and folded strata which involve most of the Paleozoic strata. The easternmost fold-thrust complex brings pre-Cambrian rocks to the surface, and is frequently considered its own province: the Blue Ridge Provence. Progressing further to the east and southeast is the Piedmont Province, characterized by highly metamorphosed rocks which were the roots of the Allegheny orogeny mountains; finally there is the Atlantic coastal plain, extending offshore as the continental shelf.

The boundary between the plateau and the valley and ridge province is a structural feature called the Appalachian Structural Front (Price, 1931; Mount, 2014), and is frequently approximately co-incident with the present-day drainage divide between the Atlantic and the Gulf of Mexico (via the Mississippi River system with its tributaries).

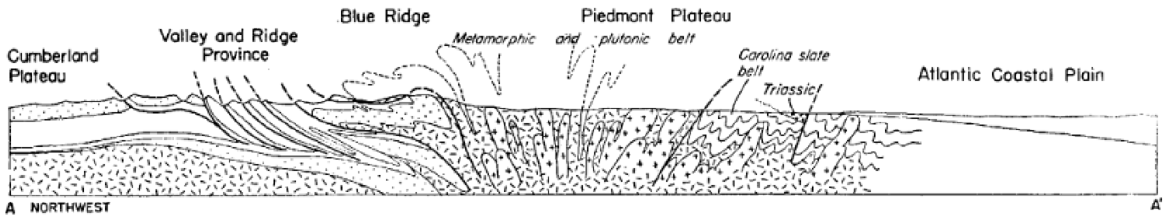


Figure 2-4 –Generalized cross-section of the Appalachian system from Kentucky to South Carolina. The major physiographic divisions are indicated. Horizontal distance is approximately 400 miles; the vertical scale is exaggerated. (after King, 1950)

With respect to hydrocarbons, the stratigraphy of the Appalachians can be divided in two. The lower part, prior to the end of the Ordovician, is primarily characterized by clastics and carbonates. The major exception for fossil fuels is the upper Ordovician Utica Shale and Point Pleasant Formation which are rich in organic material and constitute a major gas "play" (Drozd and Cole, 1992). The lower Paleozoic section is terminated by the upper Silurian Salinas Formation (Rickard, 1969). This major salt horizon was an economically important source of salt until the mid-20th century; importantly, it also is the decollement layer for thrusting of overlying sediments during the Appalachian orogeny (Frey, 1973).

The later Paleozoic stratigraphy is much more important for fossil fuels. The general pattern is thick sediments to the east-southeast with formations thinning to the west-northwest as can be seen especially for the middle Devonian in figure 2-5.

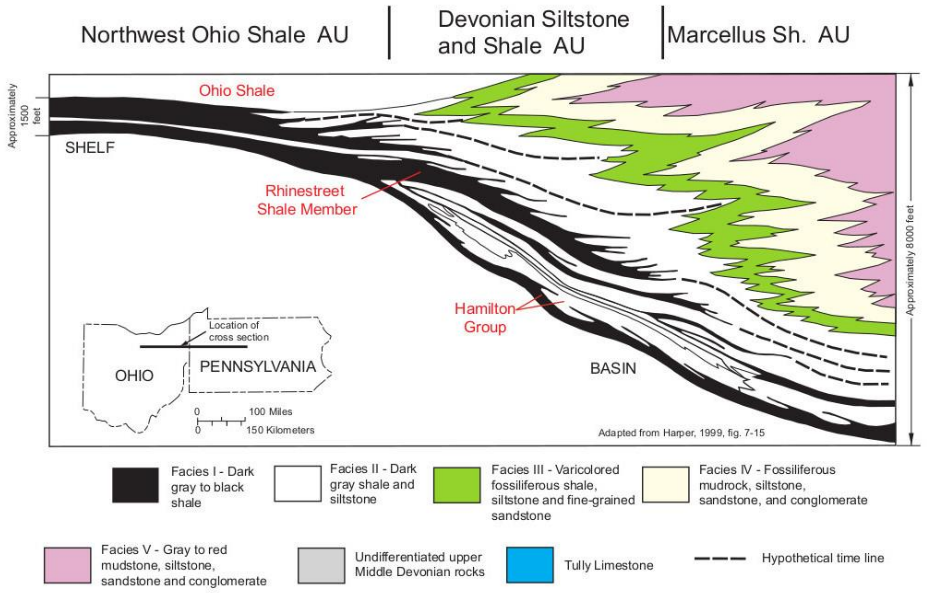


Figure 2-5 -- Cross-section of Devonian strata from central Ohio to central Pennsylvania (after Harper, 1999; Milici and Swizey, 2014). AU stands for Assessment Unit, the basis for resource estimates of the U.S. Geological Survey.

The predominant lithologies through the middle Devonian are carbonates and fine-grained clastics; from the middle Devonian to the end of the Devonian there is a thick clastic sequence known as the Catskill Delta (Woodrow and Sevon, 1985). "Delta" is a misnomer because there is no central river, but rather many smaller discharges flowing into the area providing a thick clastic wedge. During the Carboniferous the area was low-lying, with the deposition of major coal strata. Finally, in the Permian and into the Triassic the area was a major mountain chain from the collision of Gondwana and Laurentia (Ettensohn, 2008);

there are almost no sediments of Permian age, with what information there is being derived from Mesozoic and Cenozoic erosional products.

History of hydrocarbon production

Since before European settlement of the area, local populations have known that the Appalachian Basin is rich in hydrocarbons and coal. The first written mentions are by French missionaries in 1656; other early European missionaries and explorers from that time reported on both oil and gas “springs”, sometimes observed and sometimes recounting information from indigenous peoples (Wells, 1963). Black shales are organic-rich shales, with a measurable correlation between black color and organic content (Hosterman and Whitlow, 1983); the higher the percentage of organic material the darker the rock. Until the middle of the 19th century, black shales were often mistaken for coal deposits.

In 1821 gas began to be commercially produced from a hand-dug well about 8 meters deep in Fredonia, NY (Soeder, 2017). This gas was piped through the town using wooden pipes, and was sufficient for street lighting and some heating and light industry (Piotrowski and Harper, 1979). Then in 1859, “Colonel” Edwin Drake drilled a well which produced oil and started an oil rush (Harper et al, 1999a). For the remainder of the nineteenth century Pennsylvania oil production accounted for more than 50% of the world’s total (Harper et al., 1999a). The source of this oil was the Devonian black shales with the oil migrating into adjacent siltier and sandier layers where it could be exploited. Prior to the use of fracking, the economic assessment was that while considerable quantities of oil and gas remained within the shale itself, the economic potential was not great (Milici and Swezey, 2006).

Hydrocarbons have been produced commercially from the Devonian black shale sequence for over two centuries. Initially, oil, tar, and gas were by-products of shallow wells exploiting brines for salt. The Drake well, drilled in NW Pennsylvania in 1859, marks the beginning of North American oil industry (Harper, 1998), in no small part because oil was the objective, rather than simply a by-product as had been the case of earlier wells (Owen, 1975). The first North American “giant” field, a field with more than 500 million barrels of initial reserves

(Carmalt and Moscariello, 2017), was the Bradford field in northern Pennsylvania and southern New York (Carmalt and St. John, 1986), discovered in 1879.

But while the rocks were known to be hydrocarbon-rich, most of the hydrocarbon resource remained bound in the impermeable shales in which it had formed, with only the amounts that had seeped into more porous clastic layers being readily exploitable. As a result of the Arab Oil embargo in the 1970s, the US Government undertook a major research program, the Eastern Gas Shales Project, to assess the hydrocarbon potential of the Appalachian black shales (Soeder, 2017). The hydrocarbon assessment of the area by the US Geological survey (Milici and Swezey, 2006) is interesting because this recently it presumed the need for the hydrocarbons to be geologically concentrated in these more permeable reservoirs in order to be considered reserves.

Until the Spindletop discovery in 1901, in southeast Texas, the oil produced from Pennsylvania and adjacent areas of New York and Ohio constituted one of the two major petroleum producing areas of the world (the other being the area near Baku, Azerbaijan)[5]. While seams and small oil and gas deposits were found further west in the USA, in 1885 a senior executive of Standard Oil, when told by company scientists that production decline was inevitable, sold some of his shares at a discount; told that there were oil discoveries in Oklahoma and Texas he is reported to have said “are you crazy? I’ll drink every gallon of oil produced west of the Mississippi” (Yergin, 1991, p. 52). And in 1919 the US Geological Survey believed that oil production would start to decline within 3 years (Ahlbrandt, 2012).

Despite these predictions, Pennsylvania and adjacent New York state continue to produce oil; in 2021 they produced about 6½ million barrels of oil and in 2006 (pre-fracking) 231 trillion cubic feet of gas. Hydraulic fracturing has changed that; the 2021 gas production is 7,536 trillion cubic feet (data from EIA, 2022). That impermeable shales contain vast quantities of gas has been known for decades, perhaps more than a century (Soeder, 2017, p. vii). A similar problem of known hydrocarbons trapped in impermeable shales exists in the Barnett Shale in Texas. In that situation, the Mitchel Energy Company experimented with fracturing technologies to increase the permeability of the rock in the vicinity of the

[5] The Pennsylvania production was the basis for Rockefeller’s Standard Oil, while Azerbaijan was the basis for the Shell company and its affiliates. See Danial Yergin’s book *The Prize* (1991) for more history.

borehole (Hinton, 2012). Coupled with directional drilling, which had been developed in order to access fields from offshore platforms, the wells could have long horizontal stretches in contact with the resource-rich strata. The combined technologies, nicknamed ‘fracking’, proved successful in exploiting the Barnett Shale, and has since been extended to many other hydrocarbon-rich shale formations; the history of these developments is engagingly related by the *Wall Street Journal’s* oil and gas reporter (Gold, 2014).

The fracking technology was first applied to the Marcellus formation in 2004 by Range Resources (Helman, 2010). During the immediately following years, a number of companies competed for oil and gas rights. The USA is almost unique in that individual property owners are considered to have title to all the resources under their property (Jerolmack, 2021). Given the high natural gas prices in the years prior to the 2008 economic collapse, companies bid up the price offered to landowners for the permission to extract hydrocarbons. With leases in hand, the companies then proceeded to drill wells to extract and market the gas. As production was developed, the companies found that, unlike oil and gas wells in conventional fields, fracked wells tend to experience rapid production declines (Blumsack, 2020). The result is that while many people have enjoyed economic benefits from the activity of Marcellus exploitation, it is less clear that an economic analysis which includes all aspects of the exploitation supports a positive fiscal contribution to the economy (Collins and Medlock, 2017).

The Marcellus Shale

The most prolific and extensive of the Appalachian black shales is the Marcellus shale. It extends from New York State south to Virginia, and from New Jersey in the east to Ohio and Kentucky (figure 2-6). The formation outcrops in a west to east band across central New York

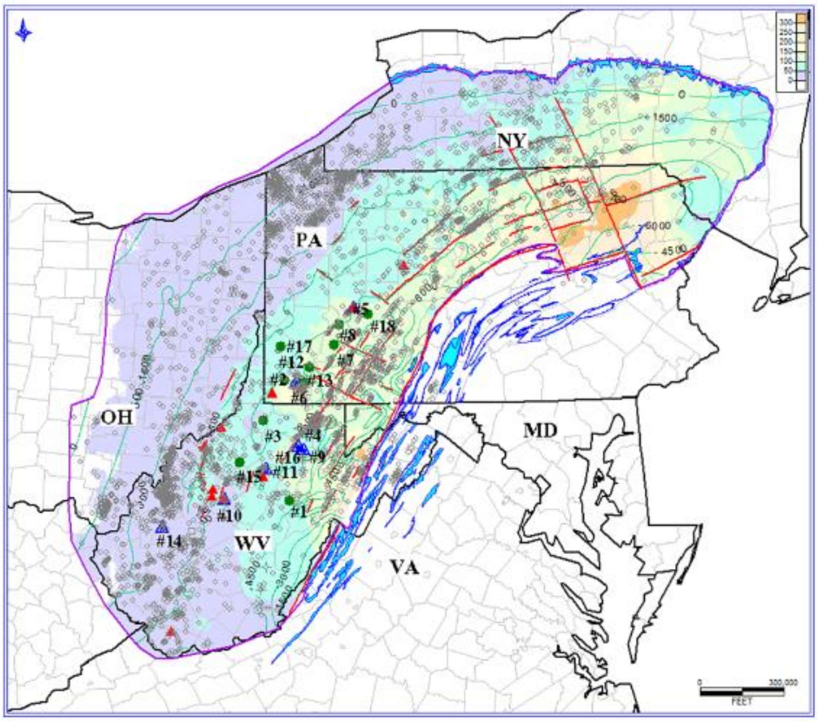


Figure 2-6 -- Extent of the Marcellus Formation (after Wang and Carr, 2012a). Outcrops are the blue band running west to east across New York State, and then turning south and southeast, and exposed in the folded part of central Pennsylvania.

State and then from northeast to southwest from northeastern New York State into Pennsylvania. In Pennsylvania and into Virginia the Marcellus outcrops where it is folded to the surface in the Valley and Ridge province; otherwise it is known from the subsurface.

Thickness varies from less than 25 feet (7.5 m) in the west to generally about 100 feet (30 m) along the southeast margins; there is an area of thicker deposition in northeast Pennsylvania and adjacent New York (up to 500 feet; 150 m) (figure 2-7)

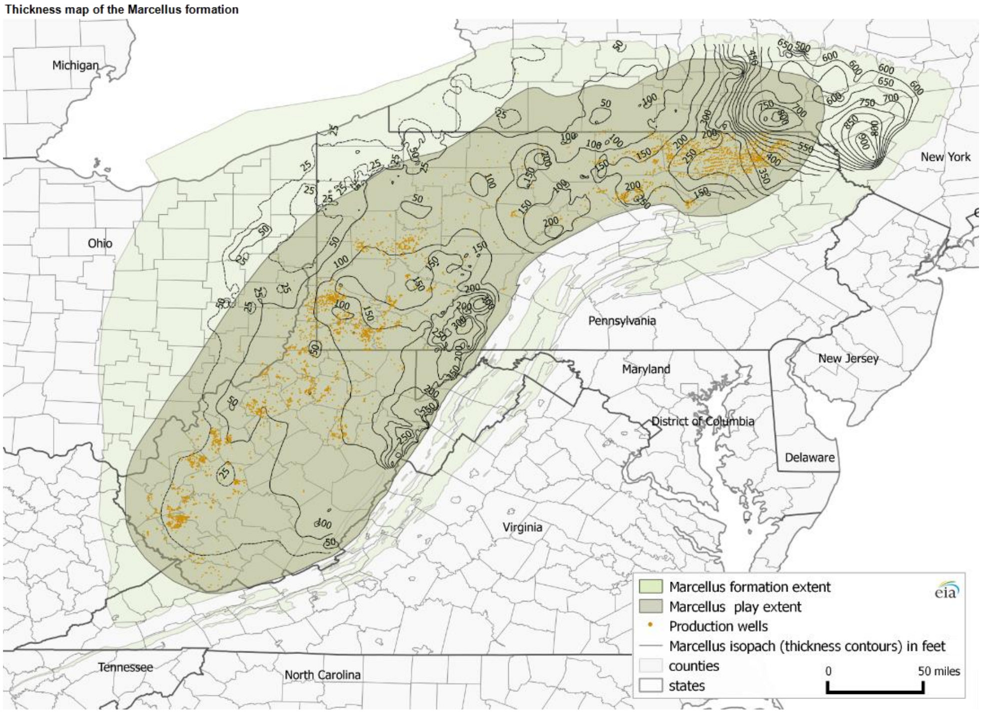


Figure 2-7 -- Extent and thickness of the Marcellus Formation (EIA, 2017)

The depositional environment was a fairly shallow, restricted circulation marine environment (Kohl, 2012, 2014); a modern analogue might be a more restricted Java Sea. Paleolatitude was about 30° south, as seen in reconstructions by Scotese and McKerrow (figure 2-8) and Blakey (figure 2-9)

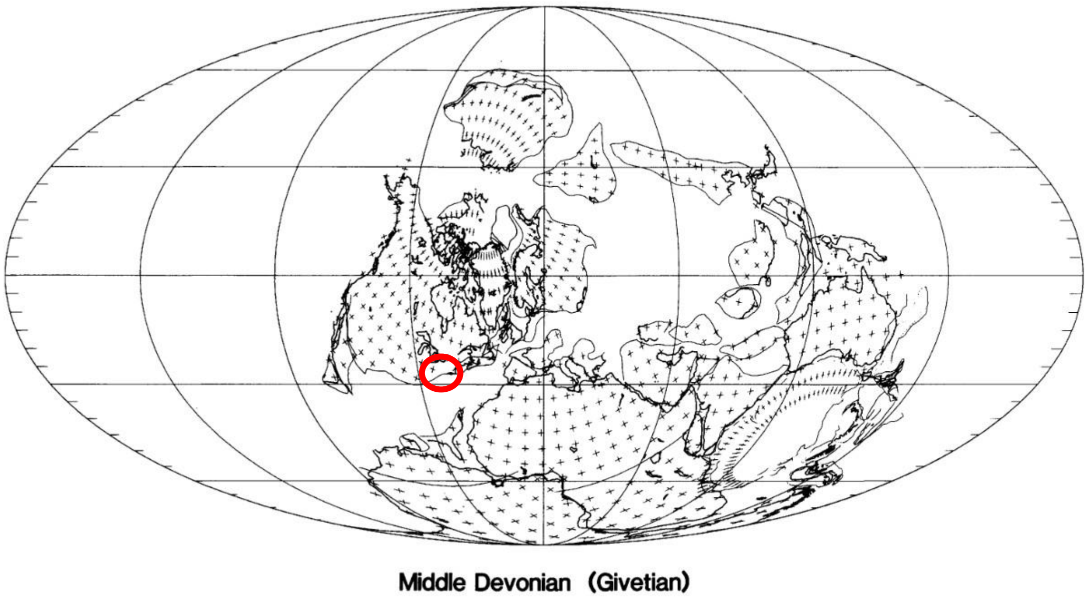


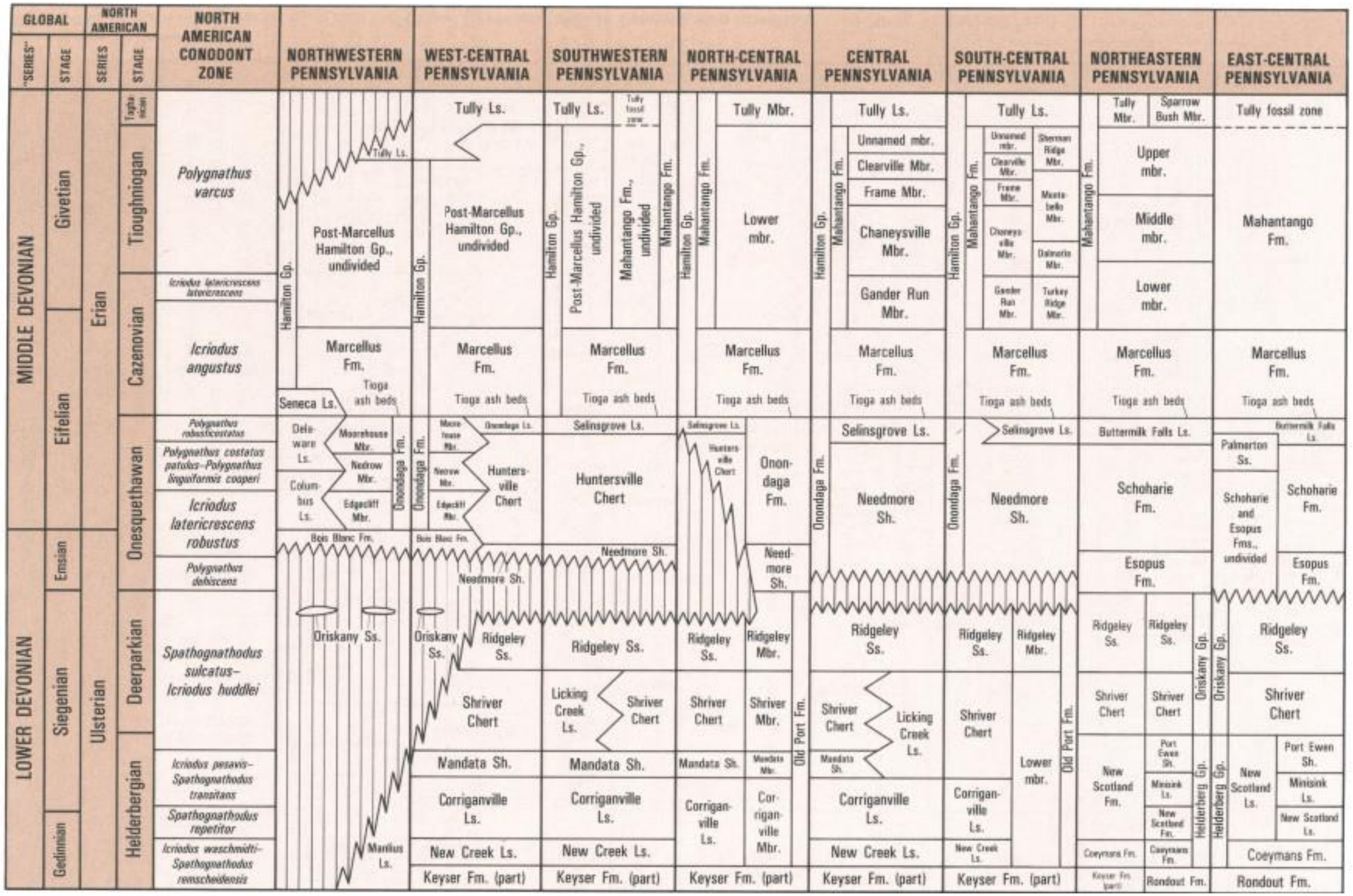
Figure 2-8 -- Middle Devonian paleoreconstruction; the red circle is the approximate area of Marcellus deposition. (after Scotese and McKerrow, 1990)

Figure 2-9 -- Paleographic reconstruction, Lower/Mid Devonian, with red circle showing area of Marcellus deposition (after Blakey, 2009)

A black shale of similar age extends south into Kentucky and Tennessee where it is known as the Chattanooga Shale (deWitt and Roen, 1985; Soeder et al, 2014).

Because this part of the United States has been explored for mineral resources since the eighteenth century, a number of local names have been used for the same rock units. There have been significant efforts to simplify the confusion, although nomenclature issues remain as can be seen in **Error! Reference source not found.** from 1999 (Harper, 1999). S ubsequently, ver Straeten and Brett (2006), and ver Staeten (2007) have further simplified naming (Kohl, 2012, 2014); amongst other equivalences they consider the Selinsgrove limestone as equivalent to the Onondaga limestone. Harper's stratigraphic table (**Error! R eference source not found.**) shows the Marcellus shale as the one consistent formation throughout Pennsylvania, with its base in the middle Eifelian. The Marcellus Formation is frequently grouped with overlying Eifelian and Givetian strata as the Hamilton Group.

Table 2-1 -- Pennsylvania stratigraphy (after Harper, 1999 and others)



The Marcellus Formation was named by James Hall in 1839 (Hall, 1839) for an occurrence in Marcellus, NY, a village 20 km southwest of Syracuse, NY. **Error! Reference source not found.** shows the outcrop that is the type locality.

Figure 2-10 -- Type locality of the Marcellus Formation, Marcellus, NY. Photo by the author at 42.97N, 76.33W degrees.

The Marcellus Shale is often further subdivided into a lower member, the Union Springs member, and an upper member, the Oatka shale member, both of which are shales (ver Straeten et al., 1994); these are separated by the Cherry Valley limestone (figure 2-11). In New York State the Union Spring, Cherry Valley and Oatka are considered formations whereas in Pennsylvania they are simply viewed as members of the Marcellus Shale formation (Kohl, 2012, 2014).

Figure 2-11 -- Cherry Valley limestone at Cherry Valley, N.Y. Photo by the author at 42.78N, 74.70W degrees.

While both the Oatka member and the Union Springs member have considerable organic material, the Cherry Valley limestone does not (Root and Jordan, 2017). In logs, the Marcellus Formation is identified by its high gamma-ray signature in logs (Eitrheim et al, 2016) as can be seen in figure 2-12. The radioactivity creates disposal problems for both drilling fluids (Lauer et al, 2018) and cuttings (Resnikoff et al., 2010).

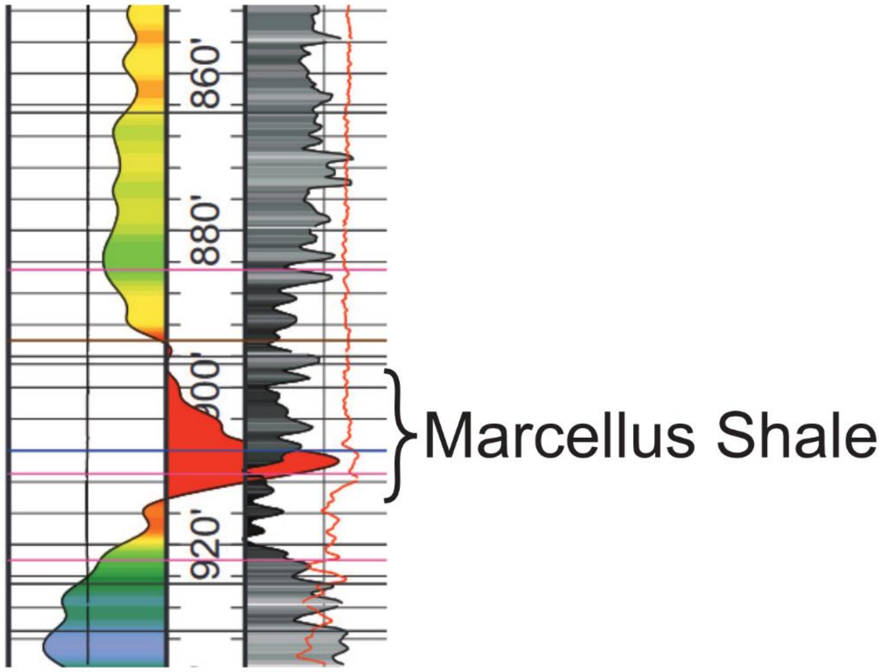


Figure 2-12 -- Section of the log from the Bald Eagle well, showing high gamma-ray interval that identifies the Marcellus Shale. A more complete portion of this log is shown in appendix B.

Organic matter is converted to hydrocarbons primarily by heat that is the result of burial, as illustrated in figure 2-9. A proxy for the temperature that the rock has reached is the vitrinite

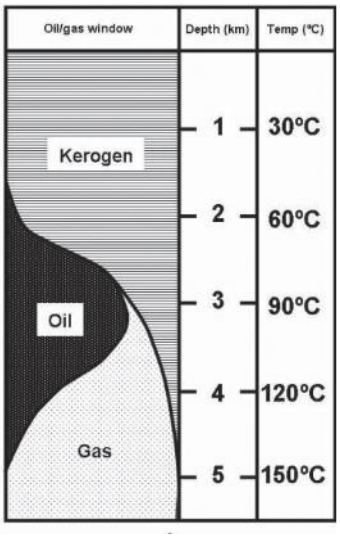


Figure 2-13 -- Oil and gas formation with depth (after Haas et al., 2013)

reflectance value, $\%R_o$ (Haas et al., 2013 amongst many). Values for the Marcellus Formation range from < 0.5 $\%R_o$ in northwest Pennsylvania to over 3.0 $\%R_o$ in northeast Pennsylvania (Repetski et al., 2002 and figure 2-10). The thermal history of a well in northeast

Pennsylvania has been modelled by

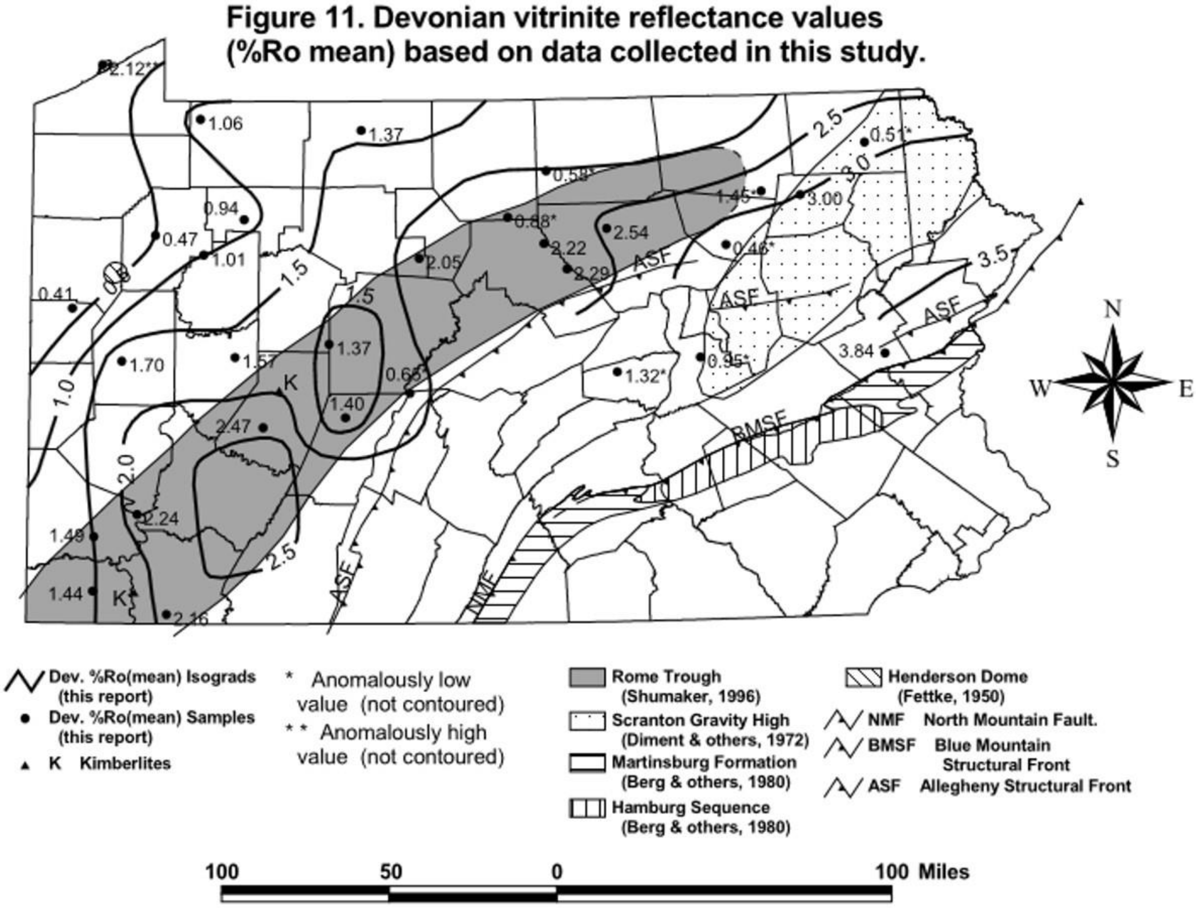


Figure 2-14 -- %R_o values for Devonian shales (Repetski et al., 2002)

Higley and Enomoto (2019)(figure 2-11). Their work shows that the Marcellus was fairly

qu

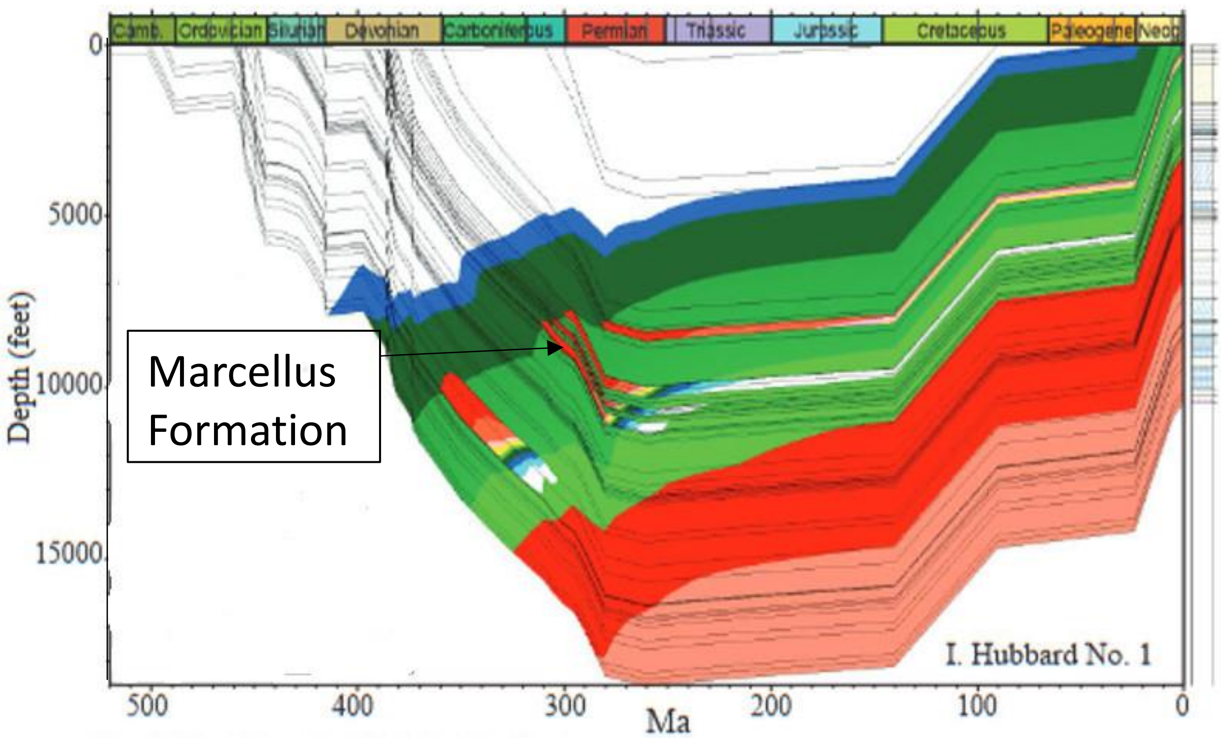


Figure 2-15 -- Burial history of the Marcellus Formation (after Higley and Enomoto, 2019) buried to depths where the heat could convert organic matter into oil and gas; by the Permian the Marcellus had reached its maximum burial depth. Unroofing by erosion occurred mostly during the Cretaceous and Neogene, leading to today's depths for the Marcellus Shale of 4,000 to 5,000 feet below the land surface.

Chapter 3 -- Marcellus Shale analytical processing

What can the geology of the Marcellus shale tell us about the occurrence of gas? When the project started it was clear that there was enthusiastic industry activity in both northeast and southwest Pennsylvania, but much less interest in the center of the state. Why? What limits did the geology of the Marcellus place on the economic viability of gas development? In addition to understanding the regional issues of Marcellus gas exploration, two specific explanations were investigated: the role of internal decollements within the Marcellus Shale, and the role of the Appalachian Front.

The project had difficulty in obtaining seismic data or well samples from the gas companies operating in Northeast Pennsylvania. Therefore Marcellus outcrops from the Valley and Ridge area of central Pennsylvania were sampled to obtain some information about possible geologic trends and controls on Marcellus gas exploitation. Figure 3-1 shows the Marcellus outcrop area and the locations of samples.

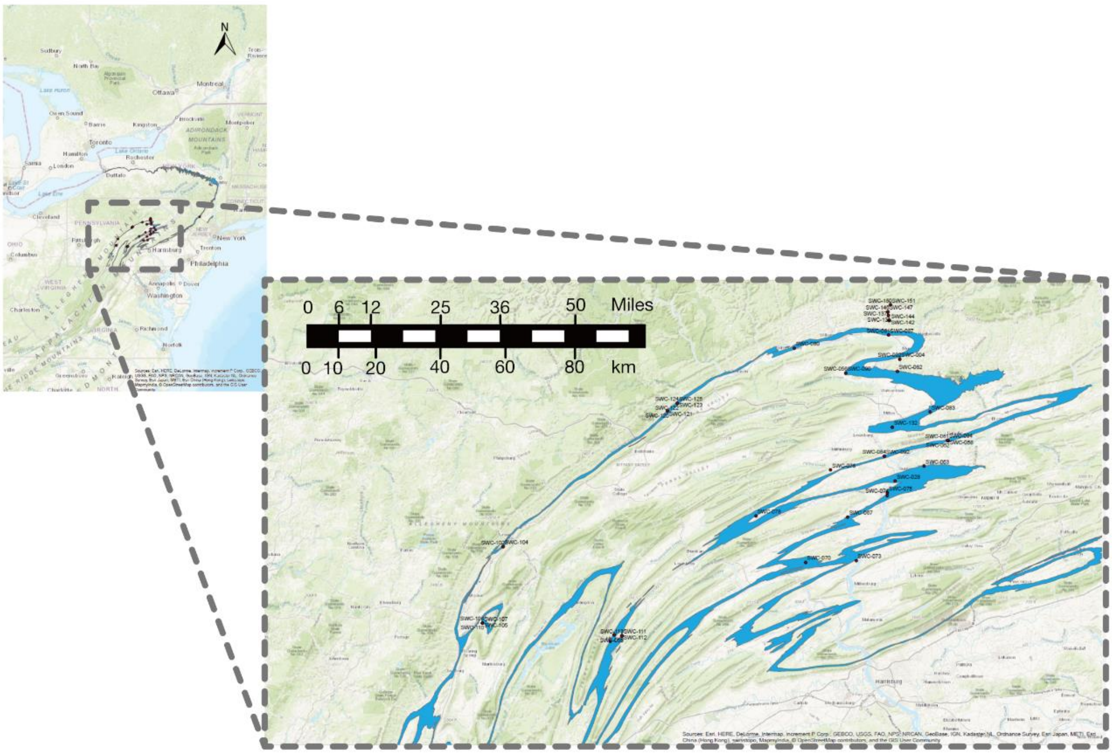


Figure 3-1 -- Map of central Pennsylvania showing Marcellus outcrops (blue) and sample locations.

Even in this area there are seldom natural exposures due to the friable nature of the shale, which makes it especially susceptible to weathering. Sample locations exposing the

Marcellus thus tend to be shallow road cuts (figures 3-2 and 3-3) and small, often abandoned, quarries (Figures 3-4 and 3-5). Most of these have the disadvantage of the Marcellus being sufficiently close to the surface that the shale has been degraded by weathering. Late in the project, one company did provide cuttings and some core from two gas wells; in addition, some unweathered samples were obtained from research cores drilled by The Pennsylvania State University in conjunction with the Pennsylvania Geological Survey.

Figure 3-2 -- Road outcrop of Marcellus shale near Kistler, PA (sample SWC-053). Photo by author at 40.369N, 77.847W.

Figure 3-3 -- Road outcrop of Marcellus shale on Cocolamus Creek Road, Juniata county. Photo by author at 40.601N, 77.148W

Figure 3-4 -- Marcellus shale in abandoned quarry near Newton-Hamilton, PA. Photo by author at 40.398N, 77.826W.

Figure 3-5 -- Marcellus shale in abandoned quarry near Elimsport, PA. Photo by author at 41.138N, 76.993W.

A list of sample collected for this study is given in Table 3-1; additional outcrop and sample photos are found in Appendix C.

Table 3-1 -- Sample data

Sample	Latitude	Longitude	Type	Short location description
SWC-001	41.247214	-76.8328	roadcrop	I-180 Hughesville - shopping center access road
SWC-002	41.177239	-76.7922	roadcrop	I-180 Muncy - anticline nose
SWC-003	41.177239	-76.7922	roadcrop	I-180 Muncy - anticline nose
SWC-004	41.177239	-76.7922	roadcrop	I-180 Muncy - anticline nose
SWC-005	41.292881	-77.0662	roadcrop	Rt. 15 north of Williamsport - Lock Haven, not Marcellus
SWC-028	40.834967	-76.8096	roadcrop	Rt. 147 south of Sunbury
SWC-029	40.835728	-76.8093	roadcrop	Rt. 147 south of Sunbury
SWC-030	40.834223	-76.8092	roadcrop	Rt. 147 south of Sunbury
SWC-031	40.834223	-76.8092	roadcrop	Rt. 147 south of Sunbury
SWC-032	40.834223	-76.8092	roadcrop	Rt. 147 south of Sunbury
SWC-033	40.834223	-76.8092	roadcrop	Rt. 147 south of Sunbury
SWC-050	40.397697	-77.8257	quarry	Newtown-Hamilton quarry
SWC-051	40.397664	-77.8256	quarry	Newtown-Hamilton quarry
SWC-052	40.39758	-77.8256	quarry	Newtown-Hamilton quarry
SWC-053	40.382153	-77.8698	roadcrop	Kisler road, Kisler; Roadcut below RR
SWC-054	40.397637	-77.8256	quarry	Newtown-Hamilton quarry
SWC-055	40.397657	-77.8256	quarry	Newtown-Hamilton quarry
SWC-056	41.138081	-76.9927	quarry	Finck quarry, near Elimsport
SWC-057	40.947383	-76.6119	roadcrop	Rt. 54 east of Riverside, road cut
SWC-058	40.94786	-76.6125	roadcrop	Rt. 54 east of Riverside, road cut
SWC-059	40.948302	-76.7632	roadcrop	Rt. 54 east of Riverside, road cut
SWC-060	40.948302	-76.6133	roadcrop	Rt. 54 east of Riverside, road cut
SWC-061	40.948433	-76.6133	roadcrop	Rt. 54 east of Riverside, road cut
SWC-062	40.949328	-76.6144	roadcrop	Rt. 54 east of Riverside, road cut
SWC-063	40.877145	-76.7017	roadcrop	Snydertown Rd. West of Snydertown

SWC-064	40.905024	-76.8492	roadcrop	Rt. 15 between Selinsgrove and Lewisburg
SWC-065	40.734255	-76.9839	roadcrop	stream along Flint Valley Rd, east of Mt. Pleasant Mills
SWC-066	40.733137	-76.9862	quarry	quarry on Flint Valley Rd, east of Mt. Pleasant Mills
SWC-067	40.733137	-76.9862	quarry	quarry on Flint Valley Rd, east of Mt. Pleasant Mills
SWC-068	40.60143	-77.1477	roadcrop	Juniata County, Cocolamus Creek Road
SWC-069	40.60143	-77.1477	roadcrop	Juniata County, Cocolamus Creek Road
SWC-070	40.605525	-77.1421	outcrop	Juniata County, Cocolamus Creek Road
SWC-071	40.605525	-77.1421	outcrop	Juniata County, Cocolamus Creek Road
SWC-072	40.605525	-77.1421	outcrop	Juniata County, Cocolamus Creek Road
SWC-073	40.610644	-76.9541	roadcrop	Cliff on west side of Rt. 15 near Rt. 147 junction
SWC-074	40.794237	-76.8388	quarry	southern of two quarries on Rt. 147, opposite Selinsgrove
SWC-075	40.801285	-76.8386	quarry	northern of two quarries on Rt. 147, opposite Selinsgrove
SWC-076	40.86676	-77.0495	roadcrop	Roadcrop on Rt. 104, Penns Creek
SWC-077	40.86676	-77.0495	roadcrop	Roadcrop on Rt. 104, Penns Creek
SWC-078	40.736682	-77.3272	roadcrop	near Bannerville
SWC-079	40.756393	-77.525	quarry	quarry Havice Valley Rd.
SWC-080	41.20794	-77.1844	roadcrop	roadcrop W. Williamsport, and north
SWC-081	41.244988	-76.8339	roadcrop	shopping center
SWC-082	41.142605	-76.8013	roadcrop	I-180 south of Muncy
SWC-083	41.029271	-76.6796	roadcrop	north of Danville
SWC-087	41.244902	-76.8335	roadcrop	Shopping center interchange
SWC-088	41.244902	-76.8335	roadcrop	Shopping center interchange
SWC-089	41.137917	-76.9926	quarry	Elimsport quarry; Cored bits
SWC-090	41.137917	-76.9926	quarry	Elimsport quarry; hand sample
SWC-091	40.904858	-76.8489	roadcrop	Roadcrop w. side of US-15, Winfield
SWC-092	40.904858	-76.8489	roadcrop	Roadcrop e. side of US-15, Winfield
SWC-093	40.904574	-76.8486	roadcrop	Roadcrop e. side of US-15, Winfield
SWC-094	40.94972	-76.6148	roadcrop	Riverside outcrop (east of bridge)
SWC-095	40.94972	-76.6148	roadcrop	Riverside outcrop (east of bridge)
SWC-096	40.94935	-76.6146	roadcrop	Riverside outcrop ; Chips from coring
SWC-097	40.94935	-76.6146	roadcrop	Riverside outcrop; Chips frm surface
SWC-102	40.649501	-78.2681	outcrop	Tyrone auto parts - bank
SWC-104	40.64987	-78.2673	outcrop	Tyrone auto parts - by nodule
SWC-105	40.433607	-78.3441	quarry	Glass Bros. Quarry
SWC-106	40.43366	-78.3441	quarry	Glass Bros. Quarry
SWC-107	40.433064	-78.3441	quarry	Glass Bros. Quarry
SWC-108	40.43366	-78.3441	quarry	Glass Bros. Quarry
SWC-109	40.433661	-78.3441	quarry	Glass Bros. Quarry
SWC-110	40.433705	-78.3441	quarry	Glass Bros. Quarry
SWC-111	40.397731	-77.8255	quarry	Chicken farm unit 9 - undeformed
SWC-112	40.397731	-77.8255	quarry	Chicken farm unit 10 -deformed
SWC-113	40.397731	-77.8255	quarry	Chicken farm unit 11 - undeformed
SWC-120	41.031778	-77.6563	core	PA SURVEY Bald Eagle 2009 - Marcellus - 862.7 ft.

SWC-121	41.031778	-77.6563	core	PA SURVEY Bald Eagle 2009 - Marcellus - 913.75 ft.
SWC-122	41.05355	-77.6195	core	PA SURVEY Bald Eagle 2015 - Marcellus - 340.7 ft.
SWC-123	41.05355	-77.6195	core	PA SURVEY Bald Eagle 2015 - Marcellus - 357.5 ft.
SWC-124	41.05355	-77.6195	core	PA SURVEY Bald Eagle 2015 - Marcellus - 422.8 ft.
SWC-125	41.05355	-77.6195	core	PA SURVEY Bald Eagle 2015 - Marcellus - 463.6 ft.
SWC-126	40.40053	-77.8546	core	Penn State - Bilger - Marcellus - 390 ft.
SWC-127	40.40053	-77.8546	core	Penn State - Bilger - Marcellus - 429.5 ft.
SWC-128	40.40053	-77.8546	core	Penn State - Bilger - Marcellus - 431 ft.
SWC-129	40.40053	-77.8546	core	Penn State - Bilger - Marcellus - 436 ft.
SWC-130	40.40053	-77.8546	core	Penn State - Bilger - Marcellus - 437 ft.
SWC-131	40.40053	-77.8546	core	Penn State - Bilger - Marcellus - 438.5 ft.
SWC-132	40.986119	-76.8198	core	Penn State - Erb - Marcellus - 760 ft.
SWC-133	40.986119	-76.8198	core	Penn State - Erb - Marcellus - 680.5 ft.
SWC-134	41.06627	-77.9043	core	Penn State - SnowShoe - Marcellus - 8701 ft.
SWC-135	41.06627	-77.9043	core	Penn State - SnowShoe - Marcellus - 8725 ft.
SWC-136	41.06627	-77.9043	core	Penn State - SnowShoe - Marcellus - 8730 ft.
SWC-137	41.29937	-76.8349	cuttings	Hamilton 1V at 8095'5"
SWC-138	41.29937	-76.8349	cuttings	Hamilton 1V at 8119'
SWC-139	41.29937	-76.8349	cuttings	Hamilton 1V at 8120.5'; possible pyrite nodules
SWC-140	41.29937	-76.8349	cuttings	Hamilton 1V at 8140'
SWC-141	41.285516	-76.831	cuttings	Hamilton 1H (South) 12950-12980' (cuttings)
SWC-142	41.285586	-76.831	cuttings	Hamilton 1H (South) 12980-13010' (cuttings)
SWC-143	41.285543	-76.8325	cuttings	Hamilton 1H (South) 13010-13040' (cuttings)
SWC-144	41.285586	-76.831	cuttings	Hamilton 1H (South) 13040-13070' (cuttings)
SWC-145	41.285637	-76.8324	cuttings	Hamilton 1H (South) 13070-13100' (cuttings)
SWC-146	41.309199	-76.8361	cuttings	Hamilton 3H (North) 11420' (cuttings)
SWC-147	41.309266	-76.8366	cuttings	Hamilton 3H (North) 11450' (cuttings)
SWC-148	41.309431	-76.8367	cuttings	Hamilton 3H (North) 11480' (cuttings)
SWC-149	41.309581	-76.8361	cuttings	Hamilton 3H (North) 11570' (cuttings)
SWC-150	41.329217	-76.8268	cuttings	Eichenlaub 4H at 12530' (end of flat) (sweep sample)
SWC-151	41.329217	-76.8268	cuttings	Eichenlaub 4H at 12546' (TD) (sweep sample)

Surface sample analyses and results

Initial processing

The general processing procedure was to prepare a thin section from a piece of the sample. Because of the friable nature of the rock the preparation of the thin section frequently required initial stabilization with epoxy. After initial examination with the scanning petrographic microscope, thin sections that were to be further analyzed by QEMScan were carbon-coated. After the thin section was prepared, some of the remaining sample was crushed and ground for x-ray diffraction and pyrolysis examinations. A few samples were prepared for nanoindentation measurements, but it proved impossible to provide sufficiently micro-smooth surfaces for this type of analysis. Finally, a few samples were prepared for vitrinite reflectance analysis. Not all samples were prepared for all analyses.

Photomicrographs and QEMScan analyses

The Marcellus shale is very fine-grained and can be rich in organic matter. Figure 3-6 shows

Figure 3-6 -- Marcellus organic-rich shale; sample SWC-056 from a quarry near Elimsport, PA. The scale at the bottom right is 5mm

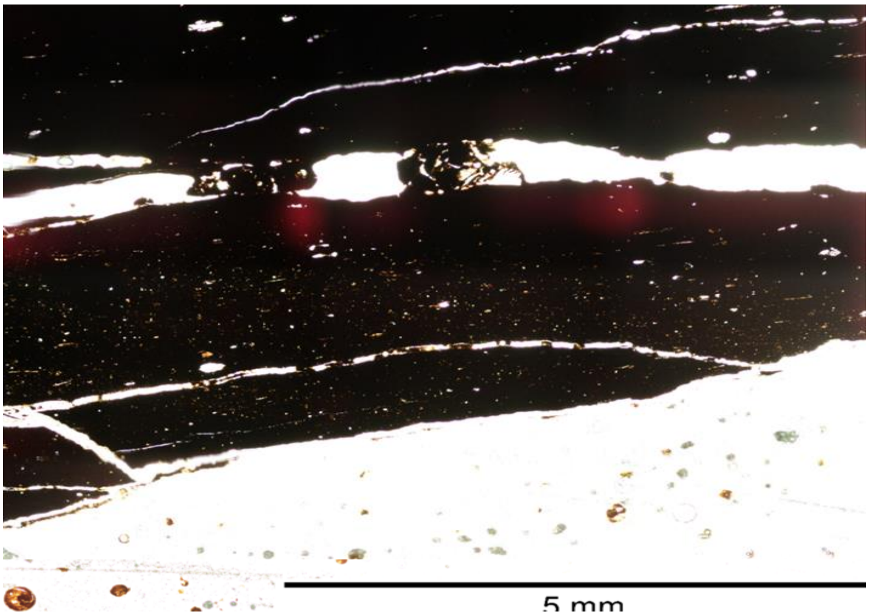


Figure 3-7 -- Detail of sample SWC-056 shown in figure 3-6

a sample stabilized by epoxy from a quarry near Elimsport. The Total organic carbon of this sample is 6.29%. Even in a detail of this sample (figure 3-7) the grain size is too fine to discern much detail.

QEMScan[6] is a technique which combines a scanning electron microscope with automated computer analysis, providing both a mineralogical analysis of the sample with a detailed false-color image. Each analyzed point produces back-scatter electrons, which depend on the elements under the electron beam at that particular point. These back-scatter electrons are automatically analyzed and from this analysis the most likely original mineral phase composition at that point is reported. The resulting mineralogy of the sample is then available both in tabular form, based on the area of the sample occupied by each mineral phase, and as a false-color image, where the mineral phases have been assigned arbitrary colors. The general scheme is to use green for clays, blues for carbonates, and pink for quartz and feldspar; yellow generally indicates pyrite, which is frequent in anoxic clay deposits (Thiel, 2018).

For sample SWC-056 shown in figures 3-6 and 3-7, the QEMScan analysis (table 3-2) shows that the clay fraction is predominately illite, with quartz and muscovite being much of the rest. The QEMScan false-color image for this sample is shown in figure 3-8.

Table 3-2 -- QEMScan mineral compositions of sample SWC-056

Mineral Name	Area%	Density	weight%
Illite	59.308	2.75	62.99
Quartz	15.702	2.63	15.92
Muscovite	9.531	2.83	10.4
Unclassified	5.077	0	0
Siderite	3.785	3.96	5.79
Fe Oxides	2.42	0	0
Background	2.002	0	0
Kaolinite	1.363	2.6	1.37
Biotite	0.907	3.1	1.09
Chlorite	0.559	3.2	0.69
Rutile	0.558	4.25	0.92
Pyrophyllite	0.304	2.85	0.33
Plagioclase	0.264	2.62	0.27
Montmorillonite	0.074	2.35	0.07
Paragonite	0.048	2.78	0.05
Glauconite	0.031	2.68	0.03
Barite	0.031	4.48	0.05
K-Feldspar	0.023	2.56	0.02

[6] QEMScan was initially developed by Australia's CSIRO and consists of a scanning electron microscope with detectors for back-scattered electrons; a proprietary computer program converts the back-scatter information into mineral phases. QEMScan is currently a licensed trademark of the FEI company.

Others	0.006	1.35	0
Zircon	0.003	4.65	0
Calcite	0.001	2.72	0
Dolomite	0.001	2.85	0
Apatite	0.001	3.19	0
Calcite-Quartz (75:25) (R)	0.001	0	0

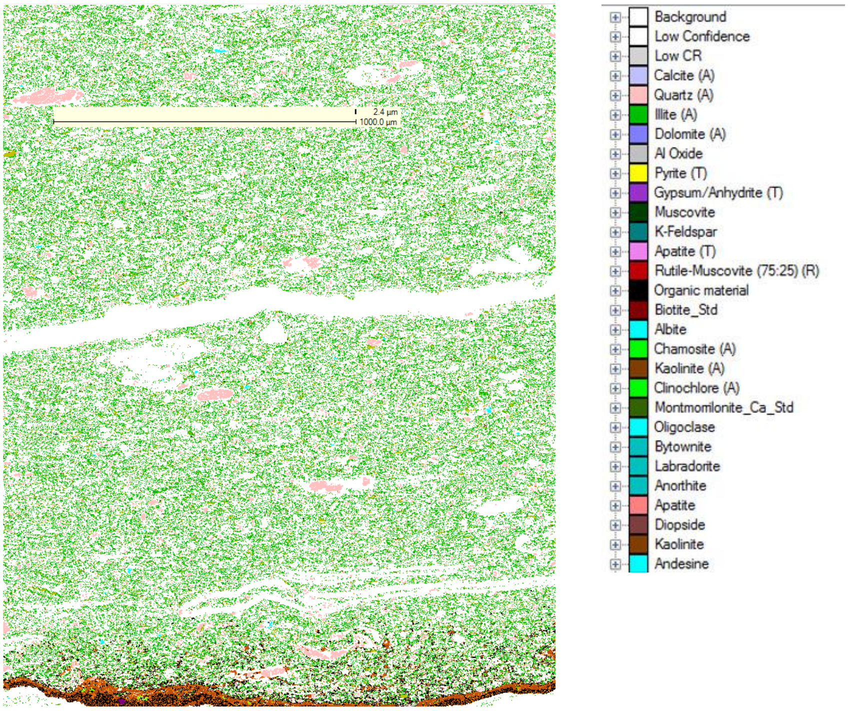


Figure 3-8 -- QEMScan false-color image of sample SWC-056

Similarly, sample SWC-058, from a road outcrop east of Riverside, PA, shows a very fine grain size, too fine to discern individual grain information. Here the QEMScan mineralogy

Figure 3-9 -- Marcellus shale sample SWC-058, road outcrop east of Riverside, PA

Table 3-3 -- QEMScan mineralogy of sample SWC-058

Mineral Name	Area%	Density	weight%	average density
Quartz	34.513	2.63	36.36	2.491624889
Illite	28.078	2.75	30.99	2.491624889
Muscovite	16.625	2.83	18.85	2.491624889
Unclassified	8.483	0	0	2.491624889
Background	4.759	0	0	2.491624889
Plagioclase	4.305	2.62	4.53	2.491624889
Chlorite	2.705	3.18	3.45	2.491624889
Biotite	1.882	3.1	2.34	2.491624889
Kaolinite	1.504	2.6	1.57	2.491624889
Fe Oxides	0.594	0	0	2.491624889
Rutile	0.564	4.25	0.96	2.491624889
Siderite	0.278	3.96	0.44	2.491624889
Montmorillonite	0.247	2.35	0.23	2.491624889
K-Feldspar	0.052	2.56	0.05	2.491624889
Pyrophyllite	0.047	2.85	0.05	2.491624889
Apatite	0.042	3.19	0.05	2.491624889
Paragonite	0.024	2.78	0.03	2.491624889
Glauconite	0.023	2.68	0.02	2.491624889
Pyrite	0.019	5.01	0.04	2.491624889
Zircon	0.009	4.65	0.02	2.491624889
Others	0.006	1.75	0	2.491624889
Calcite	0.001	2.72	0	2.491624889

(table 3-3) shows quartz, illite and muscovite as the principal components. The false-color image of sample SWC-058 is shown in figure 3-10.

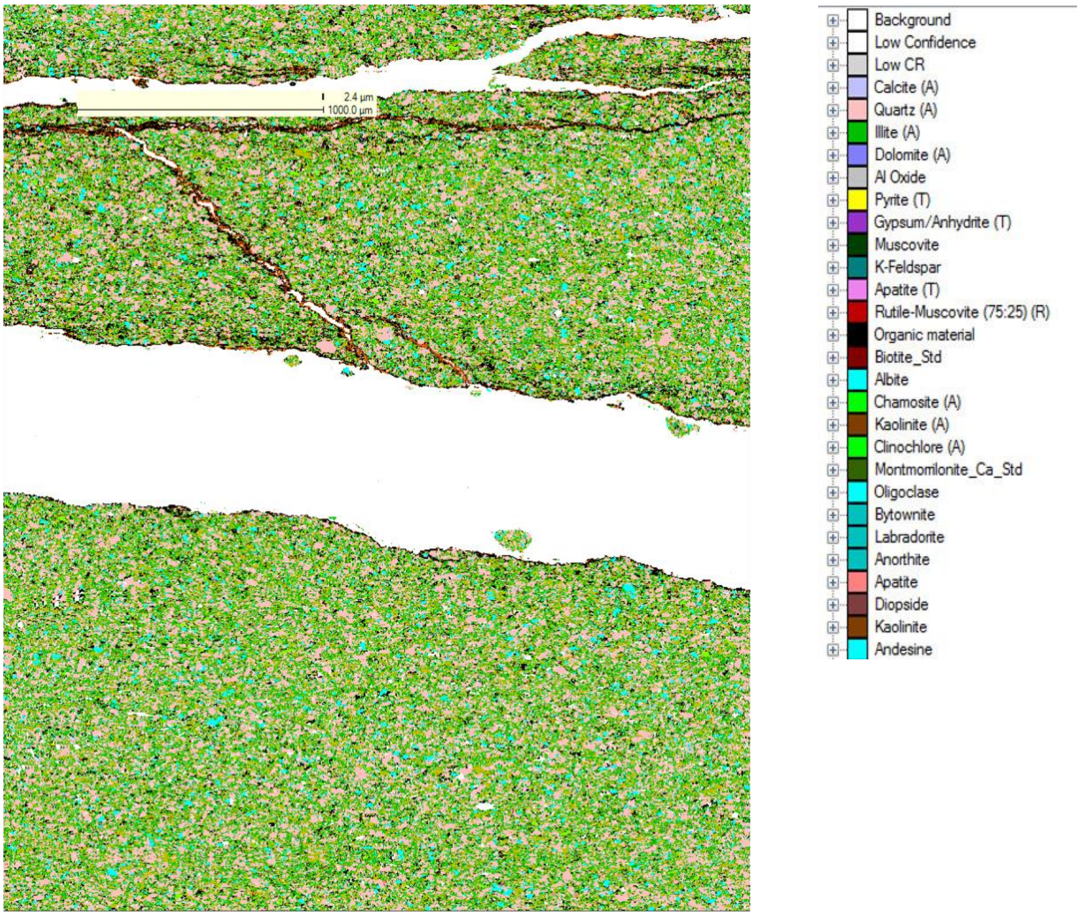


Figure 3-10 -- QEMScan false-color image of sample SWC-058

The two samples above (SWC-056 and SWC-058) are typical of the Marcellus Formation.

There are some horizons that have an abundance of equally fine-grained calcite shells (SWC-052, figures 3-11 and 3-12, table 3-4) or layers of slightly coarser clastic material (SWC-064, figures 3-13 and 3-14, table 3-5).

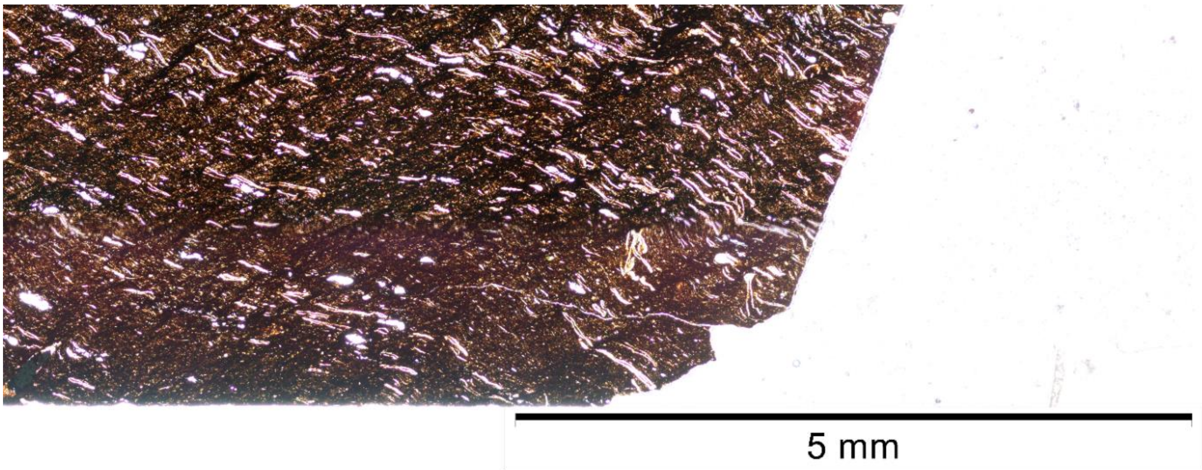


Figure 3-11 -- Marcellus sample SWC-052 from Newton-Hamilton quarry showing calcite fragments

Table 3-4 -- QEMScan mineralogy for sample SWC-052

Mineral Name	Area%	Density	weight%	average density
Calcite	40.854	2.72	43.71	2.537765962
Quartz	24.767	2.63	25.62	2.537765962
Illite	20.67	2.75	22.4	2.537765962
Calcite-Quartz (75:25) (R)	4.345	0	0	2.537765962
Dolomite	2.554	2.85	2.87	2.537765962
Unclassified	2.053	0	0	2.537765962
Background	1.763	0	0	2.537765962
Plagioclase	1.628	2.54	1.63	2.537765962
Muscovite	0.765	2.83	0.85	2.537765962
Pyrite	0.637	5.01	1.26	2.537765962
Montmorillonite	0.402	2.35	0.37	2.537765962
Chlorite	0.384	3.11	0.47	2.537765962
Others	0.302	0.82	0.1	2.537765962
Apatite	0.2	3.19	0.25	2.537765962
Rutile	0.154	4.25	0.26	2.537765962
Kaolinite	0.117	2.6	0.12	2.537765962
Zoisite	0.066	0	0	2.537765962
Titanite	0.026	0	0	2.537765962
Siderite	0.023	3.96	0.04	2.537765962
Biotite	0.02	3.1	0.02	2.537765962
Pyrophyllite	0.016	2.85	0.02	2.537765962
Paragonite	0.006	2.78	0.01	2.537765962
Epidote	0.004	3.45	0.01	2.537765962
K-Feldspar	0.003	2.56	0	2.537765962
Zircon	0.002	4.65	0	2.537765962
Ankerite	0.002	0	0	2.537765962

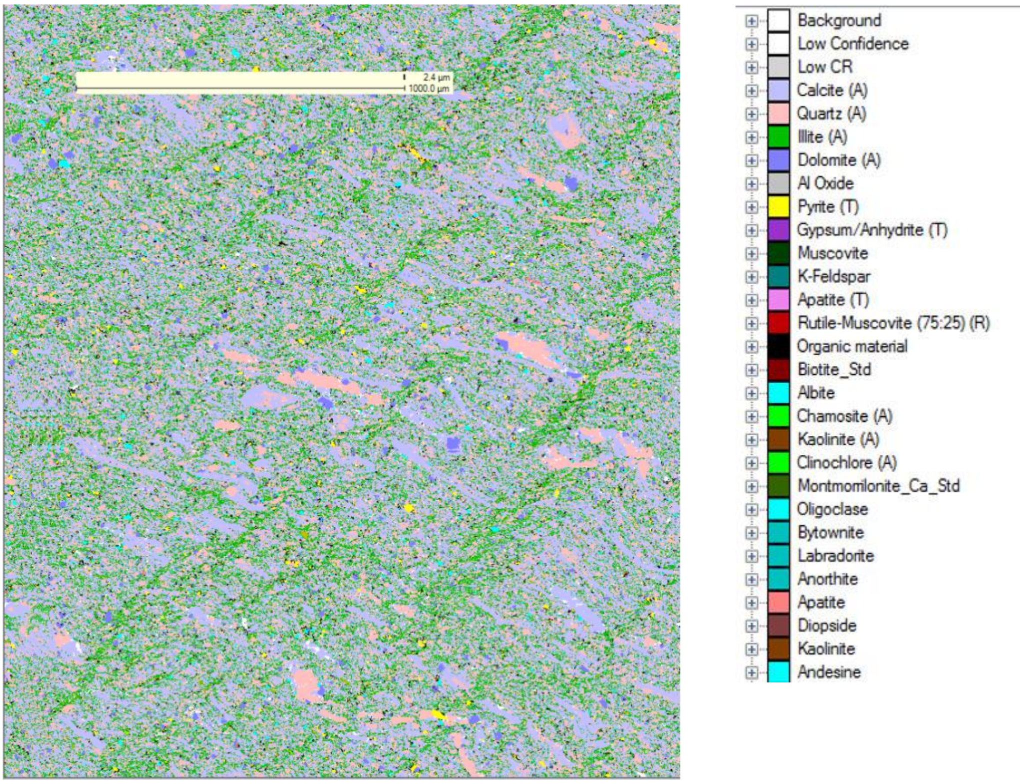


Figure 3-12 -- QEMScan false-color image of sample SWC-052 showing fine-grained calcite

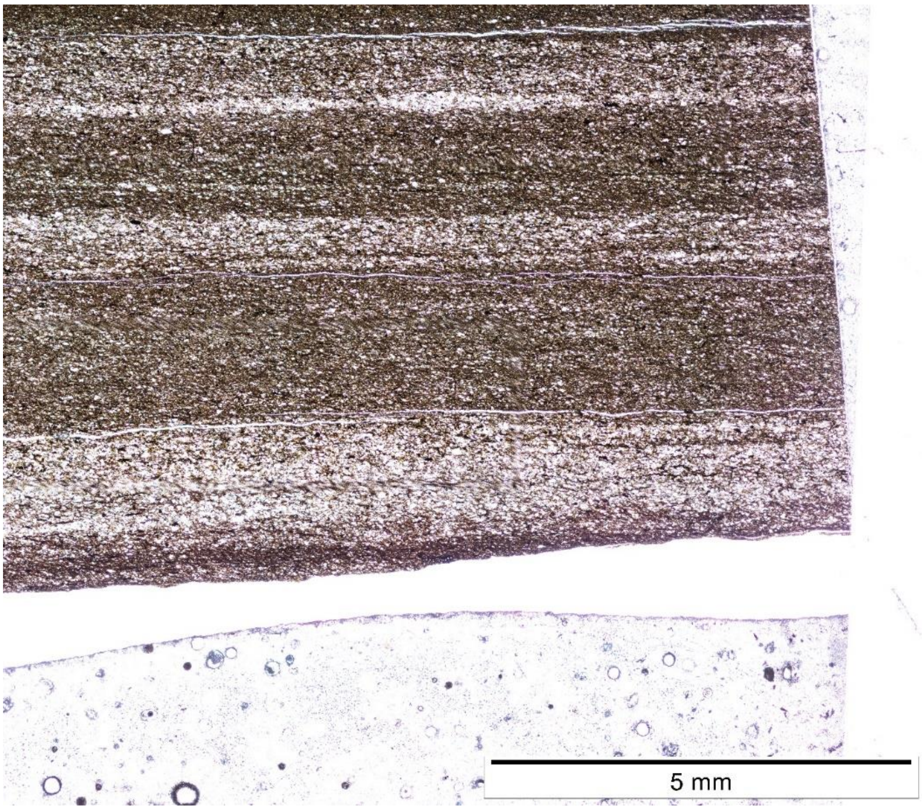


Figure 3-13 -- Sample SWC-064 from road outcrop on Route 15 near Winfield, PA, showing fine-grained clastic layers alternating with clays

Table 3-5 -- QEMScan mineralogy of sample SWC-064

Mineral Name	Area%	Density	weight%	average density
Quartz	38.026	2.63	37.48	2.663048467
Illite	25.558	2.75	26.39	2.663048467
Muscovite	15.701	2.83	16.66	2.663048467
Plagioclase	6.06	2.62	5.96	2.663048467
Background	4.791	0	0	2.663048467
Chlorite	3.902	3.18	4.66	2.663048467
Unclassified	3.479	0	0	2.663048467
Kaolinite	1.474	2.6	1.44	2.663048467
Calcite	1.449	2.72	1.48	2.663048467
Pyrite	1.341	5.01	2.52	2.663048467
Dolomite	1.035	2.85	1.11	2.663048467
Biotite	0.693	3.1	0.81	2.663048467
Rutile	0.633	4.25	1.01	2.663048467
Apatite	0.134	3.19	0.16	2.663048467
Montmorillonite	0.126	2.35	0.11	2.663048467
Calcite-Quartz (75:25) (R)	0.102	0	0	2.663048467
Pyrophyllite	0.071	2.85	0.08	2.663048467
Others	0.052	1.14	0.02	2.663048467
Paragonite	0.04	2.78	0.04	2.663048467
Ankerite	0.04	0	0	2.663048467
Siderite	0.02	3.96	0.03	2.663048467
Fe Oxides	0.018	0	0	2.663048467
Zircon	0.015	4.65	0.03	2.663048467
Zoisite	0.013	0	0	2.663048467
K-Feldspar	0.008	2.56	0.01	2.663048467
Glauconite	0.007	2.68	0.01	2.663048467
Epidote	0.002	3.45	0	2.663048467
Titanite	0.001	0	0	2.663048467
Barite	0.001	4.48	0	2.663048467

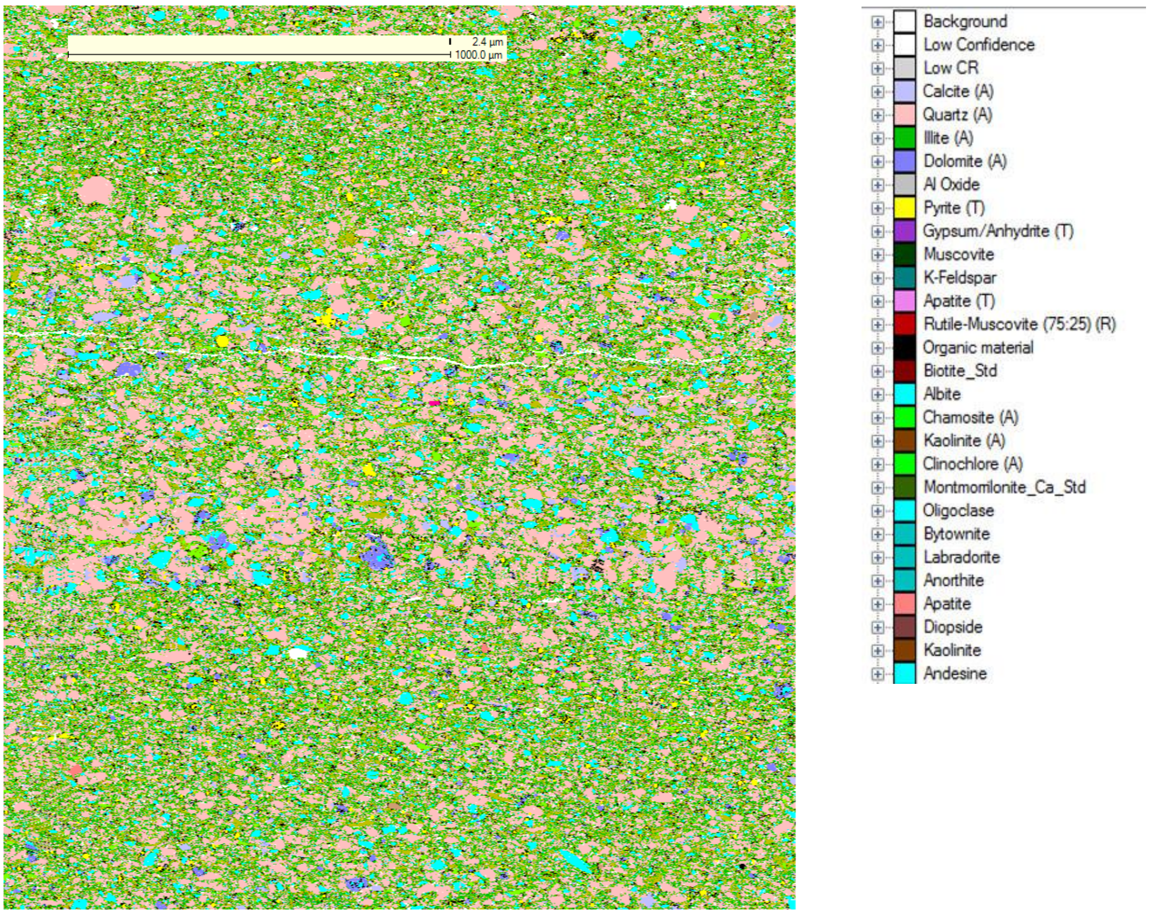


Figure 3-14 -- QEMScan false-color image of sample SWC-064 showing clastics

Figure 3-15 shows a composite of the QEMScan analyses. Most of the points shown in figure 3-15 are averages of several samples from the same outcrop. The clastics are almost entirely quartz, although there is some feldspar in some samples; the clays are primarily illite, with lesser amounts of chlorite. The clay data includes micas when present. The carbonate is generally calcite, although samples also have dolomite and siderite.

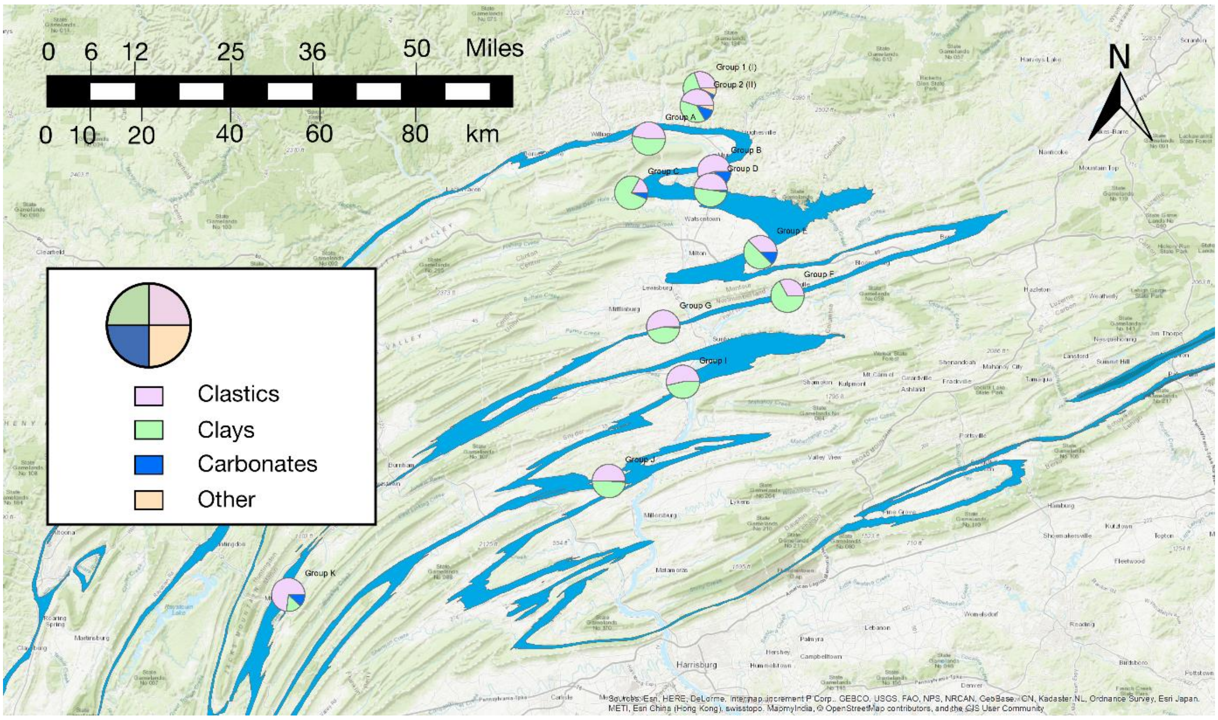


Figure 3-15 -- QEMScan mineralogy summary of Marcellus samples

The composition of the Marcellus is thus dominated by very fine clastic material. As Potter et al. (2005) observe, mud and mudstone are the products of erosion, transportation, and sedimentation (unlike carbonates which are mostly organically sourced, frequently without significant transport). Based on the QEMScan analyses, much of the Marcellus, even the clay-rich samples, is very fine-grained quartz. When plotted on a ternary diagram (e.g. Wang and Carr, 2012, Enomoto 2015) the mineralogy tends to be a mixture of clay and clastic minerals; when carbonates are present the non-carbonate continues to be a mixture. See figure 5-10. The Wang and Carr study uses cross-correlations to relate the mineralogy to total organic carbon, as shown by the color key; they were able to relate high TOC% values with samples that were a mixture of quartz and clay provided they had relatively little carbonate.

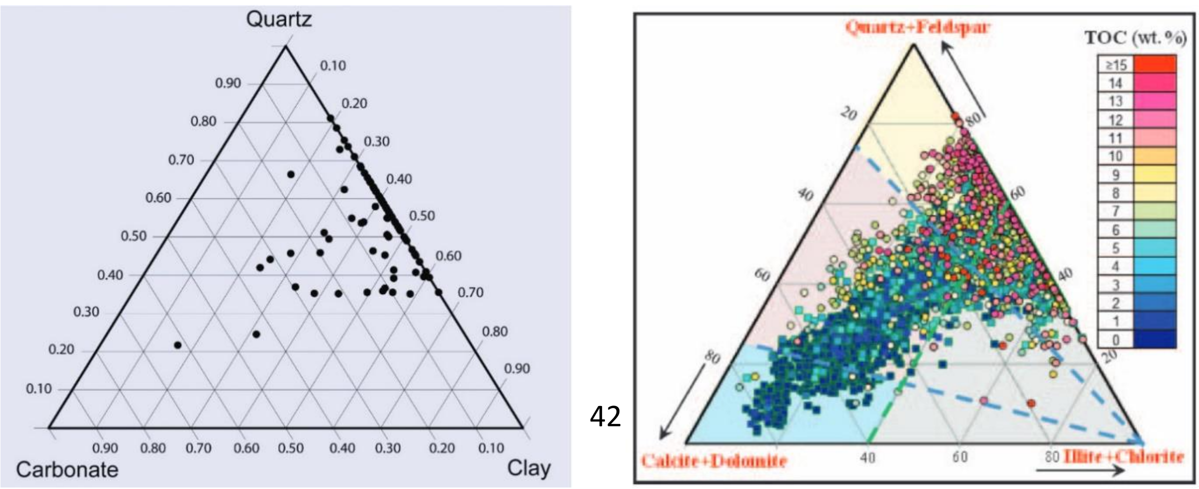


Figure 3-16 -- Marcellus mineralogy from two published studies: Enomoto et al. (2015) on left and Wang and Carr (2013) on right

These mineral distributions are similar to those found in this study, as shown in figure 3-17.

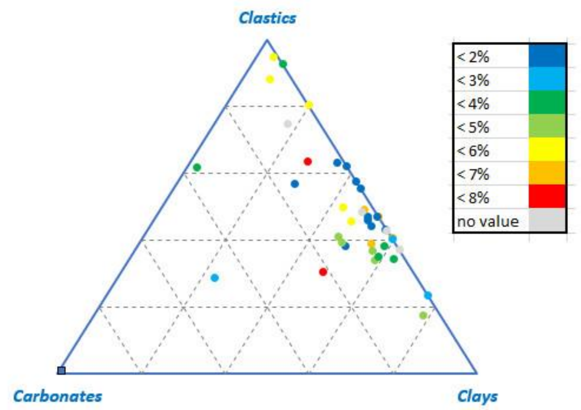


Figure 3-17 -- Marcellus mineralogy for samples in this study. Colors show the amount of TOC% from RockEval pyrolysis analyses.

Additional processing

After preparation of the thin section slides used for photomicrographs and QEMScan, some remaining material was ground in an agate morter and then sieved. Material that passed through the 63 µm mesh screen was used for both x-ray and pyrolysis measurements.

X-Ray diffraction (XRD) processing

For x-ray diffraction the department uses a Panalytical-Empyrean X-ray diffractometer (XRD). The analyses were performed in continuous scan mode using Bragg-Brentano geometry across a range of 4° to 70° 2θ using a Cu K-α source at 45 kV and 40 mA. Whole rock analyses were done directly on the <63 µm powder. For these the dry powder was loaded into the sample holder and then placed in the machine, which was programmed to run multiple samples automatically.

For specific clay analysis, the procedure followed was that outlined by Moore and Reynolds (1997). Approximately 15 grams of the <63 µm sieved powder was suspended in distilled water and the mixture placed in an ultrasound bath for at least 15 minutes to disaggregate the clays. For acidic samples (pH < 6.0) a few drops of sodium hexametaphosphate was added. The resulting mixture was the centrifuged at 800 rpm for 2 minutes, which placed all of the the >2 µm at the bottom of the tube, with the liquid containing only material <= 2 µm. This liquid was then transferred to an evaporating dish and allowed to evaporate to concentrate the clays. The concentrated clay slurry was then transferred to glass slides by pipette and allowed to dry completely, leaving an oriented clay coating on the glass slide which was used directly in the diffractometer. Analysis of the x-ray peaks was done using the HighScore Plus software of Panalytical Corporation.

The mineralogy shown by the XRD analyses consists primarily of clastics. Even the textured samples prepared with the <= 2 µm fraction showed primarily clastic rather than clay minerals. The QEMScan mineralogy is considered more useful than that shown in the XRD data.

Pyrolysis (RockEval) measurements

For the pyrolysis measurements between 5 and 10 grams of material was sent to the laboratory of Professer Dr. Thierry Adatte at the University of Lausanne, which uses a Rock-Eval 6 pyrolyser by Vinci Technologies for the analyses.

Pyrolysis analysis for hydrocarbons, developed primarily by the Institut Français du Pétrole (Espitalié et al, 1985a, 1985b, 1986), provides a rapid assessment of the hydrocarbon potential of a rock sample and requires a minimal amount of material. The technique involves heating a sample to 300°C in an inert atmosphere (N_2 is used) and measuring the hydrocarbons expelled; this measurement, termed S1, indicates the hydrocarbons already present in the rock sample as hydrocarbons. The temperature is then increased gradually and hydrocarbons created and released during this phase of the analysis are also measured; these S2 measurements indicate organic matter which has not matured naturally into hydrocarbons, but which has the potential to do so. Finally the sample is heated in an atmosphere that approximates air (N_2 80%, O_2 20%) and the amount of C released is reported as the S3 measurement. The procedures are described with specific reference to the Rock Eval 6 pyrolyser used for these samples in papers by LaFargue et al. (1998) and Behar et al. (2001). The process is automated, with results being calculated as part of the process; see Table 1 in Ordoñez et al. (2019) for details of the S1, S2 and S3 calculations.

Inorganic carbonate minerals may also break down during the pyrolysis heating. The most common carbonate minerals, calcite and dolomite, begin to break down at the temperatures used in the final stage of the analysis. But siderite will also break down during the second

Table 3-6 -- RockEval pyrolysis results

Sample	PC [%]	RC [%]	TOC [%]	MINC [%]	HI [mg HC/g TOC]	OI [mg CO2/g TOC]	Tmax [°C]	S1 [mg HC/g]	S2a [mg HC/g]	S2b [mg HC/g]	S3
SWC-002	0.01	0.29	0.30	0.88	19	96	321	0.01	0.06	0.00	0.29
SWC-004	0.01	0.28	0.29	0.74	4	54	603	0.01	0.01	0.00	0.16
SWC-028	0.00	0.72	0.73	0.50	1	2	307	0.02	0.01	0.00	0.02
SWC-051	0.22	4.86	5.08	0.63	1	156	511	0.00	0.03	0.00	7.90
SWC-052	0.13	2.15	2.28	5.04	51	43	339	0.09	1.17	0.00	0.99
SWC-053	0.02	0.76	0.78	0.33	13	49	597	0.02	0.10	0.00	0.38
SWC-054	0.08	3.71	3.79	0.18	5	59	606	0.01	0.20	0.00	2.22
SWC-055	0.22	5.41	5.63	0.58	0	140	485	0.00	0.02	0.00	7.89
SWC-056	0.13	6.16	6.29	0.24	1	71	607	0.00	0.06	0.00	4.44
SWC-058	0.02	0.87	0.89	0.05	5	60	350	0.01	0.04	0.00	0.54
SWC-061	0.09	0.95	1.04	0.15	14	270	471	0.01	0.15	0.00	2.80
SWC-062	0.22	2.48	2.70	0.51	36	188	419	0.03	0.96	0.00	5.08
SWC-064	0.01	0.26	0.27	0.96	4	97	590	0.01	0.01	0.00	0.26
SWC-067	0.02	0.53	0.54	0.06	0	105	344	0.00	0.00	0.00	0.57
SWC-070	0.01	0.19	0.20	0.31	5	129	561	0.00	0.01	0.00	0.26
SWC-073	0.01	0.19	0.20	0.01	0	136	419	0.00	0.00	0.00	0.27
SWC-074	0.01	0.67	0.68	0.02	0	31	601	0.00	0.00	0.00	0.21
SWC-075	0.10	5.41	5.51	0.22	1	63	427	0.01	0.04	0.00	3.47
SWC-076	0.02	0.24	0.25	0.03	8	188	420	0.01	0.02	0.00	0.47
SWC-078	0.06	1.95	2.01	0.11	11	70	592	0.02	0.23	0.00	1.41
SWC-080	0.03	0.27	0.30	0.04	11	366	470	0.00	0.03	0.00	1.09
SWC-081	0.01	2.54	2.55	0.02	0	6	606	0.00	0.01	0.00	0.16
SWC-083	0.03	0.27	0.30	1.23	32	230	418	0.00	0.09	0.00	0.69
SWC-084	0.01	0.34	0.35	0.05	15	38	319	0.02	0.05	0.00	0.13
SWC-086	0.01	0.25	0.26	2.83	12	80	595	0.01	0.03	0.00	0.21
SWC-087	0.04	2.47	2.51	0.12	2	37	599	0.09	0.06	0.00	0.92
SWC-090	0.02	5.02	5.04	0.09	2	7	605	0.03	0.09	0.00	0.36
SWC-092	0.02	1.47	1.49	0.06	3	36	605	0.01	0.04	0.00	0.53

SWC-094	0.01	0.32	0.32	0.03	6	34	587	0.01	0.02	0.00	0.11
SWC-107	0.30	8.14	8.45	0.19	37	4	461	0.42	3.10	0.00	0.36
SWC-108	0.20	5.13	5.33	0.31	33	5	444	0.54	1.77	0.00	0.26
SWC-109	0.08	2.46	2.54	0.12	20	9	423	0.32	0.51	0.00	0.23
SWC-110	0.10	2.99	3.09	0.09	22	6	422	0.46	0.68	0.00	0.20
SWC-111	0.07	6.52	6.59	0.17	6	17	611	0.04	0.40	0.00	1.11
SWC-112	0.04	4.86	4.90	0.35	3	19	610	0.03	0.16	0.00	0.92
SWC-113	0.06	6.42	6.48	0.21	6	15	610	0.03	0.38	0.00	0.97
SWC-120	0.14	2.10	2.24	0.39	64	6	461	0.25	1.43	0.00	0.14
SWC-121	0.29	3.71	4.00	2.91	78	6	463	0.27	3.11	0.00	0.24
SWC-122	0.15	1.75	1.90	0.45	77	5	463	0.37	1.46	0.00	0.10
SWC-123	0.34	4.38	4.72	2.30	77	5	467	0.39	3.65	0.00	0.24
SWC-124	0.18	2.05	2.23	1.96	74	6	465	0.50	1.65	0.00	0.13
SWC-125	0.39	4.64	5.03	5.24	81	6	470	0.50	4.09	0.00	0.30
SWC-137	0.12	7.47	7.59	3.56	11	7	326	0.44	0.84	0.00	0.50
SWC-138	0.15	5.37	5.53	0.82	16	6	304	0.84	0.89	0.00	0.33
SWC-139	0.06	7.14	7.20	1.63	7	6	362	0.14	0.47	0.00	0.47
SWC-140	0.05	3.30	3.36	5.91	11	11	333	0.15	0.37	0.00	0.38
SWC-141	0.86	4.14	5.00	1.89	63	8	359	7.04	3.14	0.00	0.42
SWC-142	0.79	3.73	4.52	0.91	66	9	368	6.42	2.97	0.00	0.41
SWC-143	0.96	5.14	6.10	1.01	59	7	349	7.88	3.58	0.00	0.43
SWC-144	1.04	5.12	6.16	0.95	62	7	400	8.50	3.84	0.00	0.41
SWC-145	1.03	5.27	6.29	0.98	60	7	377	8.48	3.78	0.00	0.42
SWC-146	0.60	3.00	3.60	0.69	62	15	414	4.80	2.21	0.00	0.52
SWC-147	0.63	2.84	3.47	0.56	70	9	415	5.07	2.42	0.00	0.32
SWC-148	0.77	2.87	3.64	0.52	81	14	411	6.13	2.95	0.00	0.53
SWC-149	0.95	3.63	4.58	0.88	81	16	419	7.51	3.73	0.00	0.74
SWC-150	0.95	2.93	3.88	0.49	95	14	419	7.63	3.67	0.00	0.56
SWC-151	0.45	3.05	3.50	0.55	52	7	298	3.50	1.81	0.00	0.25

stage. The automated computer processing makes the appropriate calculations as determined in the calibration studies conducted by LaFargue and Behar referenced above. The importance of these calculations is the resulting TOC% figure, which is the percentage of the sample which is organic carbon (calculated grams of Total Organic Carbon per gram of sample material). Also important are the calculated Hydrogen Index (HI), which is the milligrams of hydrocarbons per gram of TOC, and Oxygen Index (OI), which is the milligrams of measured CO_2 per gram of TOC. Table 3-6 shows all of the RockEval analysis data. A cross-plot of the HI vs. OI is very similar to the maturation paths for coal macerals from different types of organic source material (Krevelen, D.W. van, 1961); Tissot and Weldt (1984) term such HI vs OI plots 'van Krevelen diagrams'.

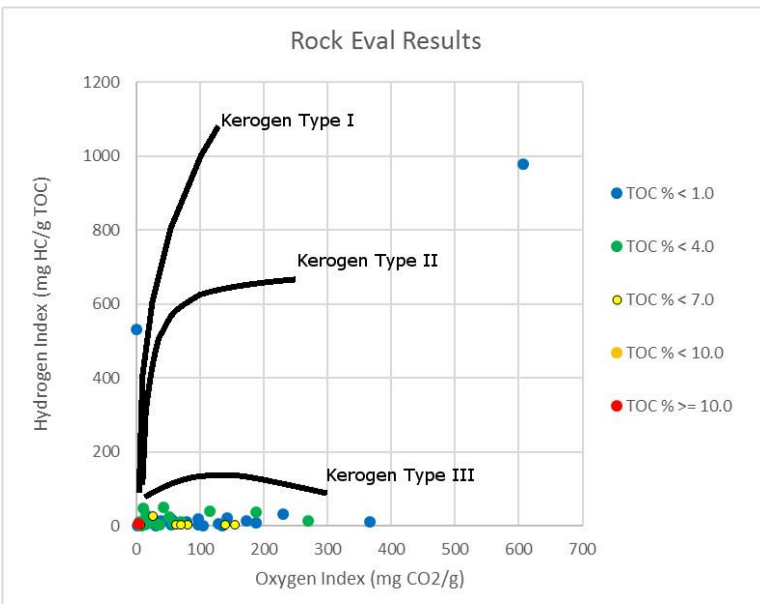


Figure 3-18 -- Hydrogen and Oxygen indices for samples in this study

Figure 3-19 shows the samples of this study plotted on such diagram, with the TOC% indicated by color. All of the samples show a very low hydrogen index (the two exceptions in the plot are from a reconnaissance trip outside the study area) indicating that the samples are significantly weathered. This extensive weathering makes it difficult to infer much about the maturation pathway of the Marcellus organic matter.

The variation in TOC% is significantly greater, even within the Marcellus/Union Springs interval. Values range from 0% to 12%, although only a few exceed 7%. Within the Lower Marcellus, the stratigraphic control was not sufficient to establish any pattern relating the organic richness to stratigraphic position; a few samples from below the Marcellus and above the Lower Marcellus do indicate that the organic richness is highest in the Lower Marcellus strata. But overall, the RockEval analyses obtained in this study do not shed much light on the internal variation of organic richness within the Marcellus "play".

In summary, the Marcellus shale consists of very fine clastic material, clay size particles, but with a mineralogy that includes considerable clastic components but relatively little carbonate. There were no regional differences in the character of the Marcellus rocks sampled that provided fresh insights into Marcellus gas occurance.

Specific data discussion -- Effect of decollements within the Marcellus shale

Two specific sites provided an ability to test suggestions about geologic control of Marcellus shale gas distribution. The first suggestion is that Marcellus productivity depends, at least in part, on the extent of underlying Silurian evaporates (Rickard, 1969; Smith and Leone, 2010; Zagorski et al, 2012). Without the salt, the layers within the Marcellus become the decollement horizons for Appalachian thrust faulting. One such decollement layer is observed in the Forgy quarry, which is a bit east of the small borough of Newton Hamilton (see figure 3-19).

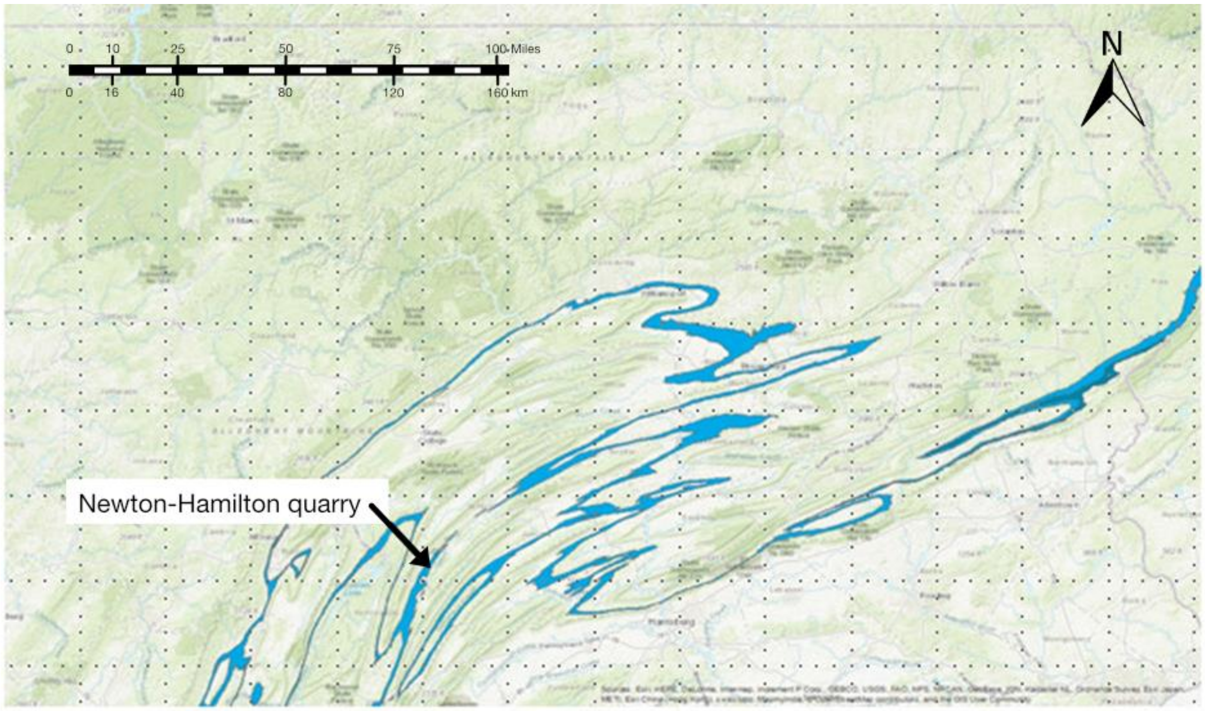


Figure 3-19 -- Location of the Forgy (i.e., Newton-Hamilton) quarry

The quarry exposes the lowermost portion the Union Springs member of the Marcellus Formation; the quarry floor is the underlying Onondaga limestone (see figure 3-4). The quarry section is slightly over 4 meters of the lower Marcellus; a nearby research well (Bilger) is located 2.5 km east of the quarry where it penetrated 55 meters of lower Marcellus (Kohl, 2012).

The bedding in the quarry has been described in detail by Bracht (in Engelder et al, 2011, Figure 28; and Kohl, 2012). Of interest here are the three topmost beds exposed in the quarry, which illustrate the Appalachian decollement within the Marcellus formation; see figure 3-20.

Figure 3-20 -- Shear zone within the lower Marcellus formation at the Newton-Hamilton quarry.

The three layers were sampled for clay mineralogy and pyrolysis examination, which showed that the deformed layer is different with respect to both its clay mineralogy and with respect to the organic material.

Figures 3-21, 3-22 and 3-24 show the XRD traces for these three layers. As can be seen, the zones above and below the shear zone have very similar mineralogies, consisting principally

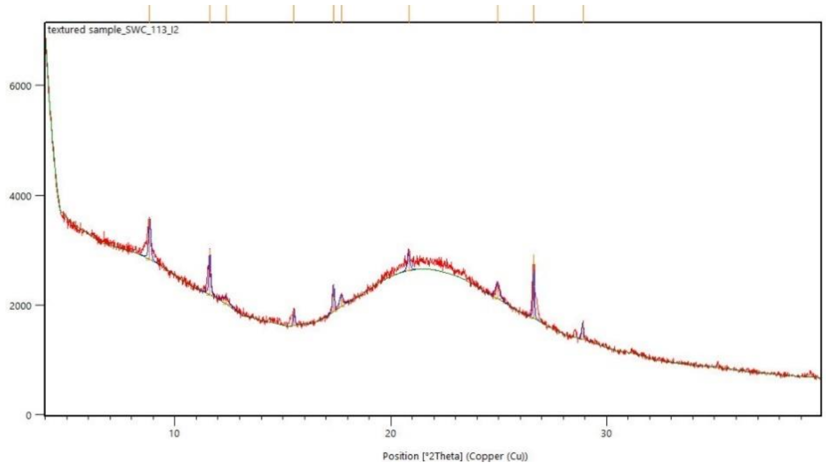


Figure 3-21 -- XRD trace for clay fraction of sample SWC-113 (top layer, Newton Hamilton quarry)

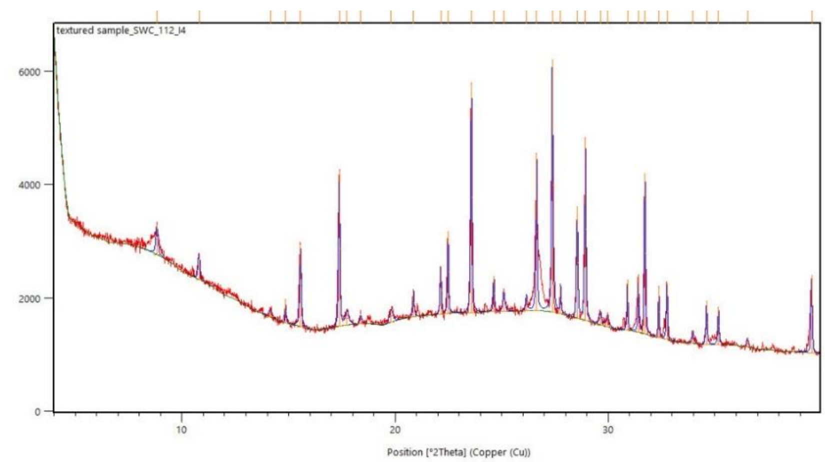


Figure 3-22 -- XRD trace for clay fraction of sample SWC-112 (middle layer Newton Hamilton quarry)

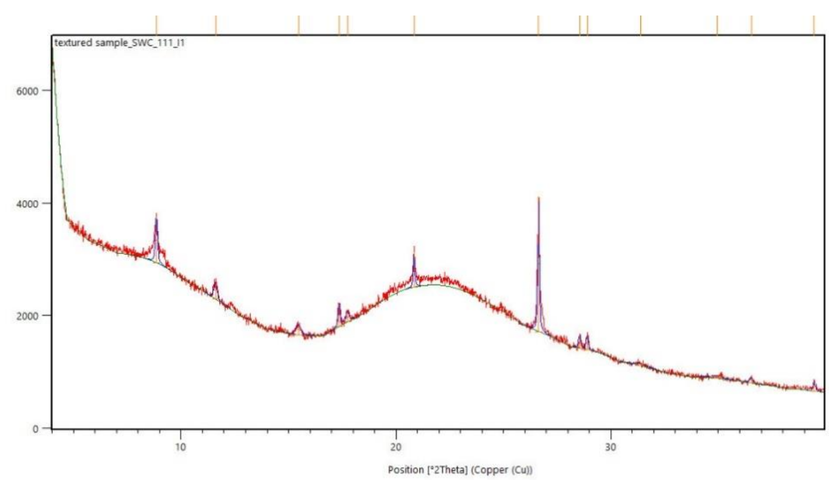


Figure 3-23 -- XRD trace for clay fraction of sample SWC-111 (bottom layer Newton Hamilton quarry) of quartz, illite, and gypsum, with some kaolinite and possibly an iron-analogue to gypsum. But the mineralogy of the middle shear zone is rather different, with quartz and muscovite being readily identified, and a number of proposed peak matches from various uncommon oxides.

Table 3-7 -- Pyrolysis data for the three layers from the Newton-Hamilton quarry

	Sample SWC-113 (top)	Sample SWC-112 (middle - shear zone)	Sample SWC-111 (bottom)
eTOC%	6.48	4.90	6.59
S1	0.03	0.03	0.04
S2	0.38	0.16	0.40
S3	0.97	0.92	1.11
Tmax	610	610	611
HI	6	3	6
OI	15	19	17

Similarly, the RockEval data, shown in Table 3-7, indicates similar top and bottom layers, with the middle layer having lower values for TOC%.

It seem likely that the disturbance of the shear or decollement zone has partially destroyed the trapping of gas within the normally impermeable layers of the Marcellus shale.

Specific data discussion -- Effects of the Appalachian structural front

Some authors, notably Laughley (2011, 2022) and Zagorski et al. (2012) have suggested that underlying tectonic features, notably the Appalachian structural front, play a major role in limiting Marcellus gas occurrence in northeast Pennsylvania. Late in the project, Inflection Energy Corporation LLC provided cuttings from three wells located near the Appalachian front in Lycoming county, data of which were compared with data from the Erb research well drilled by The Pennsylvania State University south of the front.

The Inflection wells were drilled from a single pad: the Hamilton 1 pilot well is essentially vertical, the Hamilton 1H is a lateral going essentially south from the pad, and the Hamilton 3 is a lateral going essentially north from the pad (see fig. 3-24). The north lateral is approx. 6,715 feet (2,047 m) in plan view, and the south lateral is 5,563 feet (1,696 m), giving an overall section of over 2 miles (3.7 km). These wells are just north of the boundary between the Appalachian Plateau and the Valley and Ridge provinces.

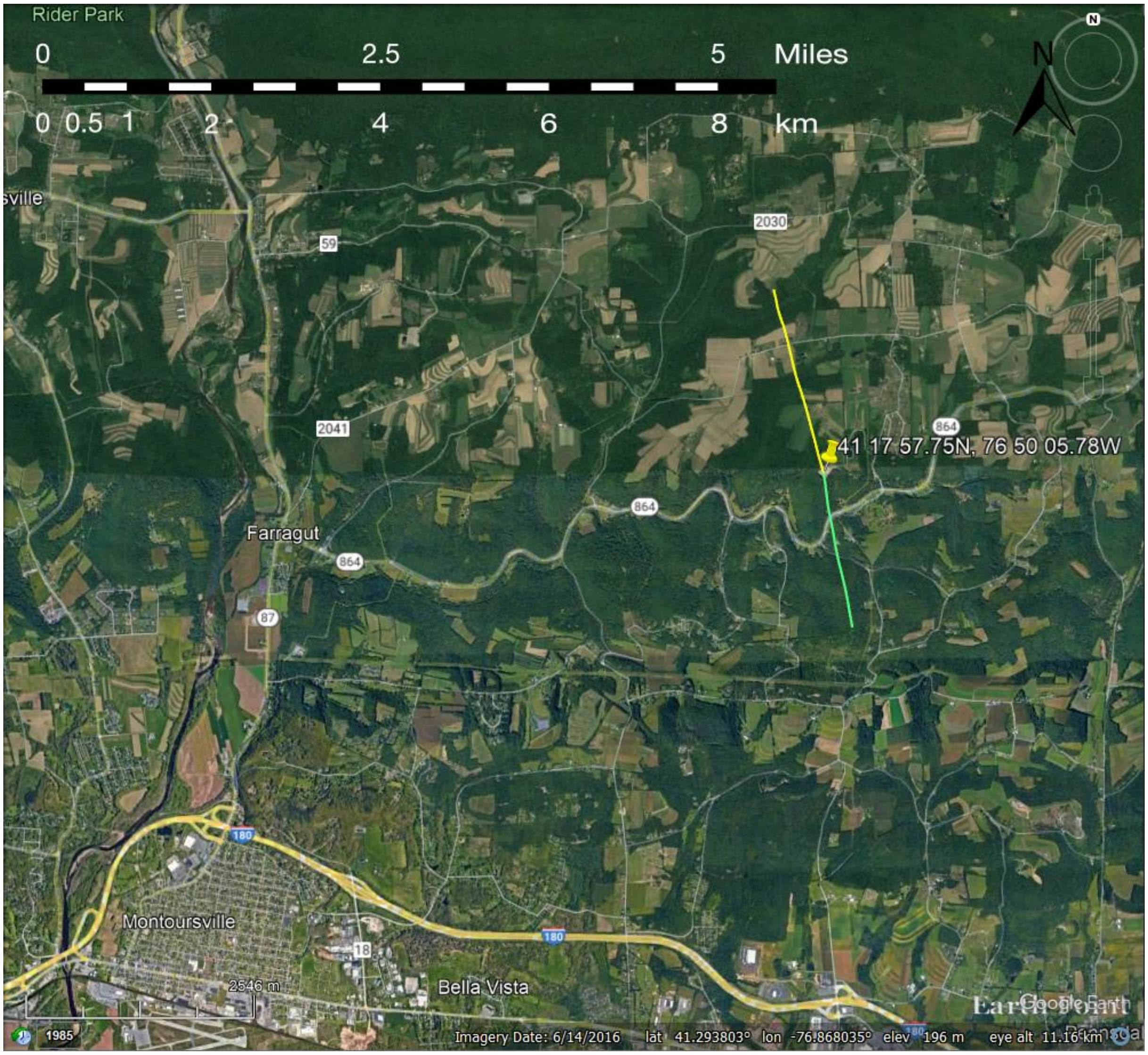


Figure 3-24 -- Location of the Hamilton pad wells; the yellow pin marks the location of the drill pad, the green line is the south lateral (Hamilton 1H) and the yellow line is the north lateral (Hamilton 3).

The borough of Montoursville in the lower left of figure 3-24 is 7.5 kilometers due east of Williamsport, Pa.

Figure 3-25 is a section plotted from the well logs of these two wells, and the approach to the Allegheny Front can be seen by the rise of strata at the south end of the Hamilton 1H well.

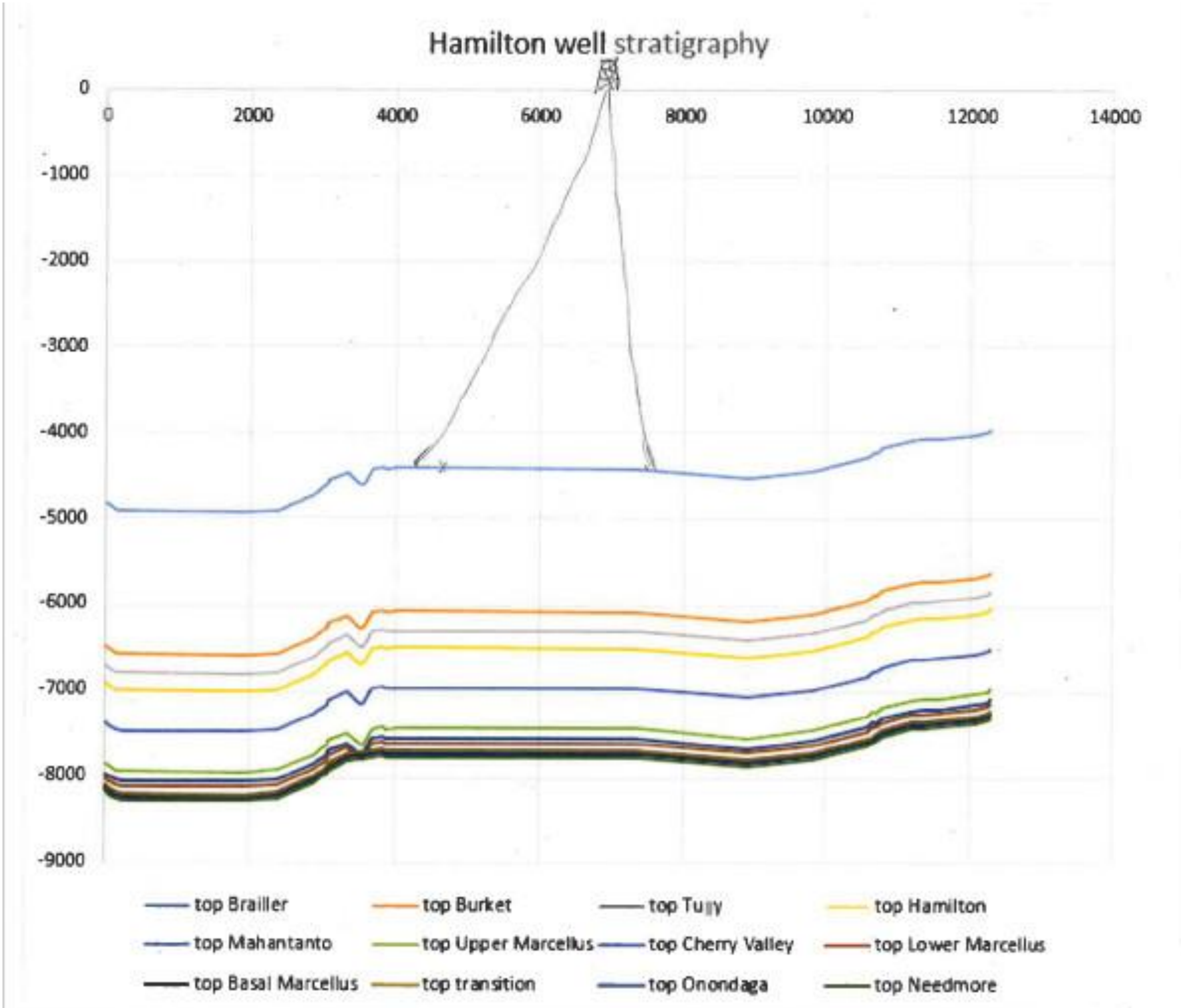


Figure 3-25 -- Formation tops from the Hamilton 1H (right) and Hamilton 3 (left) wells. View is essentially looking east, with north at the left and south at the right.

Analytical data are from cuttings gathered near the ends of the laterals plus material from a core taken from the initial pilot well drilled vertically from the pad (Hamilton 1V). Sample SWC-147 is from near the end of the north lateral (to the left in figure 3-25), SWC-144 is from near the end of the south lateral (to the right in figure 3-25), and SWC-139 is from the pilot well (approximately in the center of figure 3-25). One question concerning the occurrence of natural gas in the Marcellus Formation is the question of whether the Appalachian Front is a controlling feature.

Figures 3-26, 3-27 and 3-28 show the logs of the Marcellus section in these three wells.

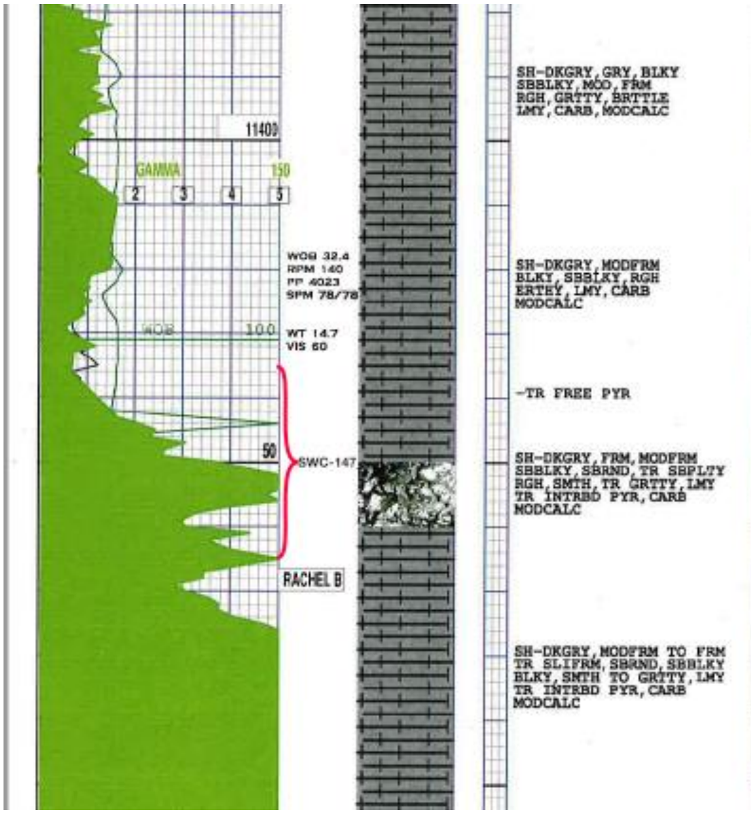


Figure 3-26 -- Part of log for Hamilton 3 (north horizontal) showing location of sample SWC-147 cuttings

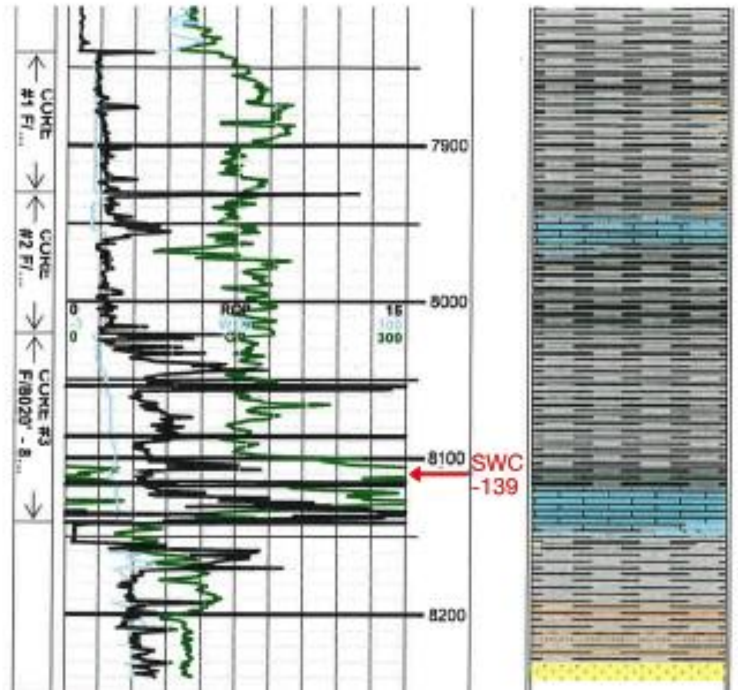


Figure 3-27 -- Part of log for Hamilton 1V (vertical) showing location of core sample SWC-139

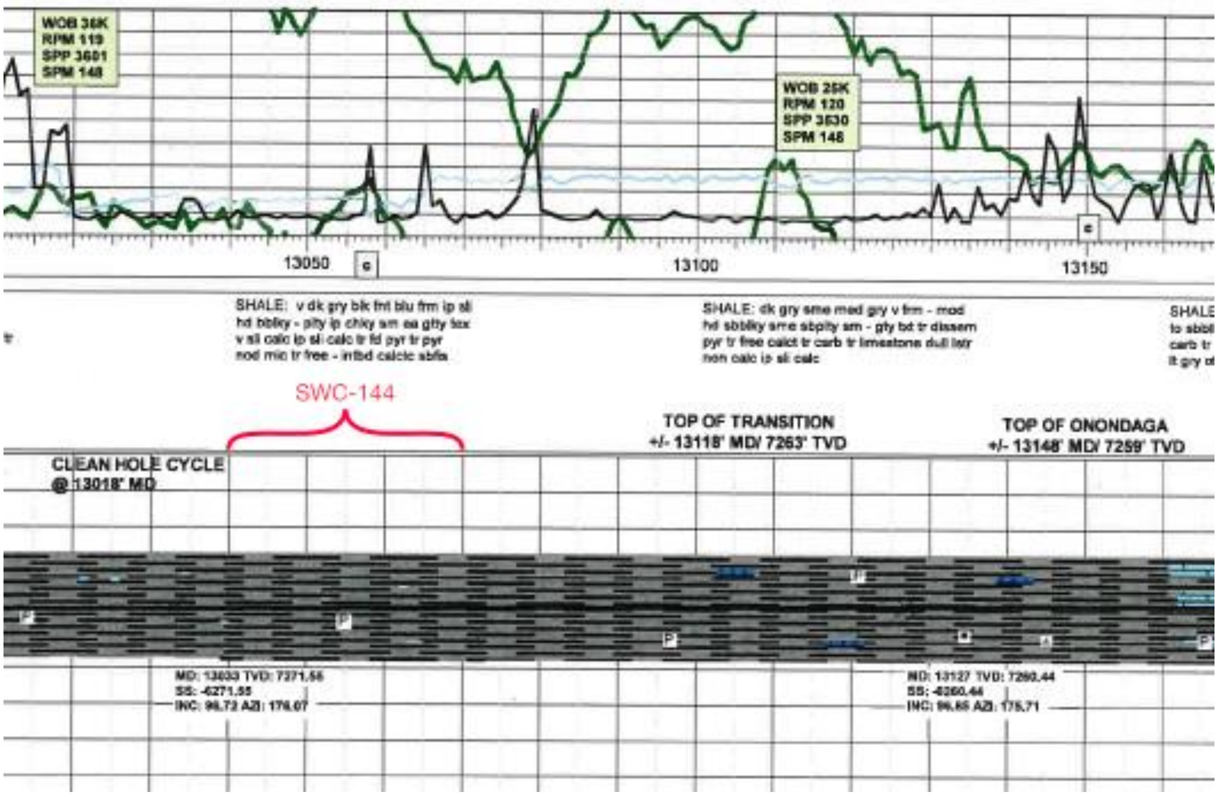


Figure 3-28 -- Part of log of well Hamilton 1S (south lateral) showing location of cuttings for sample SWC-144

The QEMScan images for these sample are shown in figures 3-29, 3-30, and 3-31

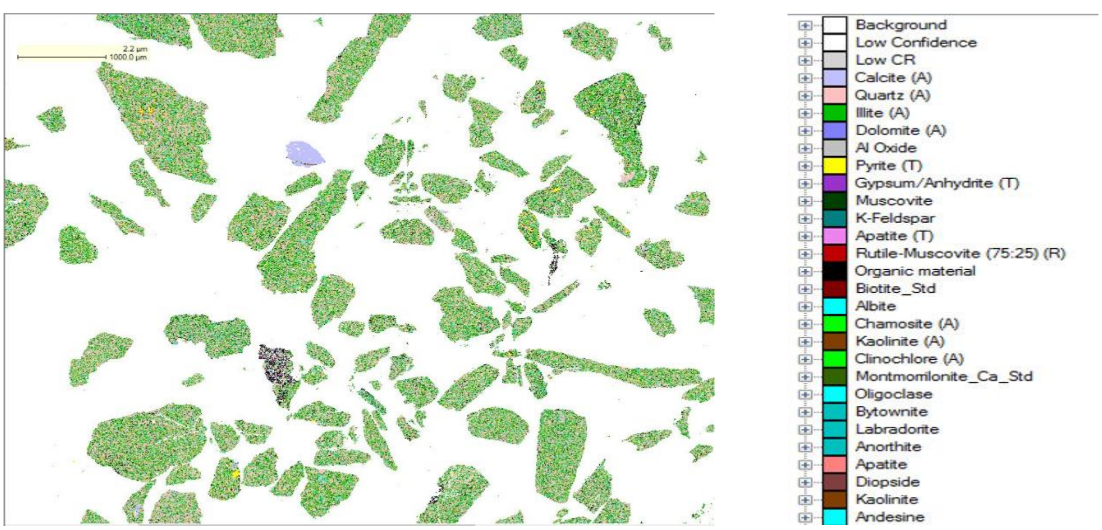


Figure 3-29 – QEMScan false color image of cuttings from end of Hamilton 3 well (north lateral), sample SWC-147

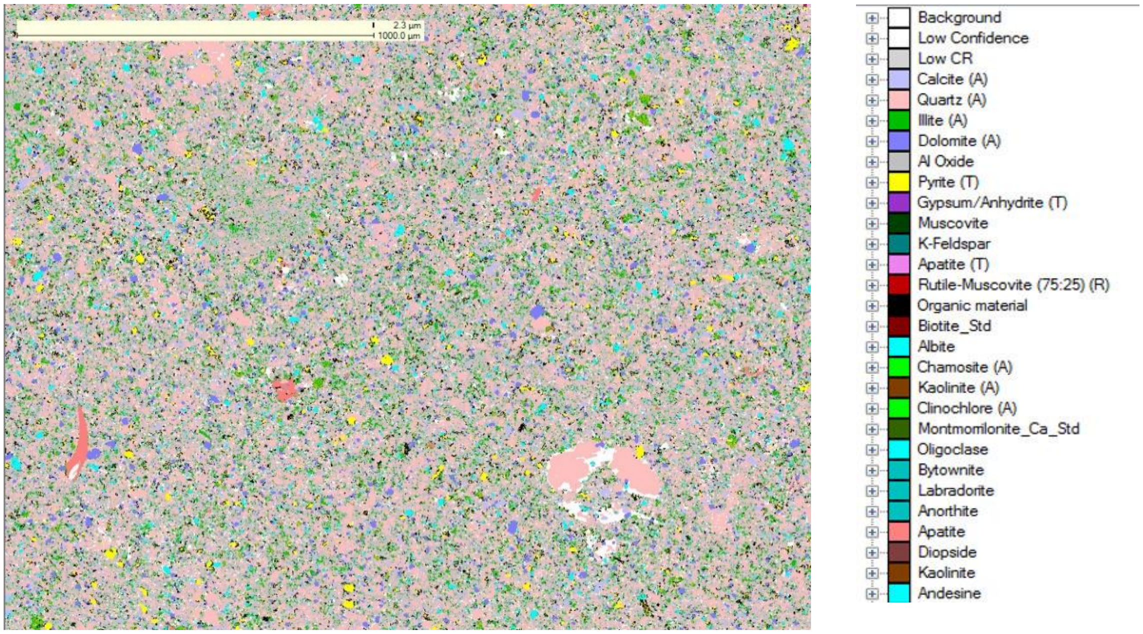


Figure 3-30 – QEMScan false color image of section from core of pilot well Hamilton 1 (sample SWC-139)

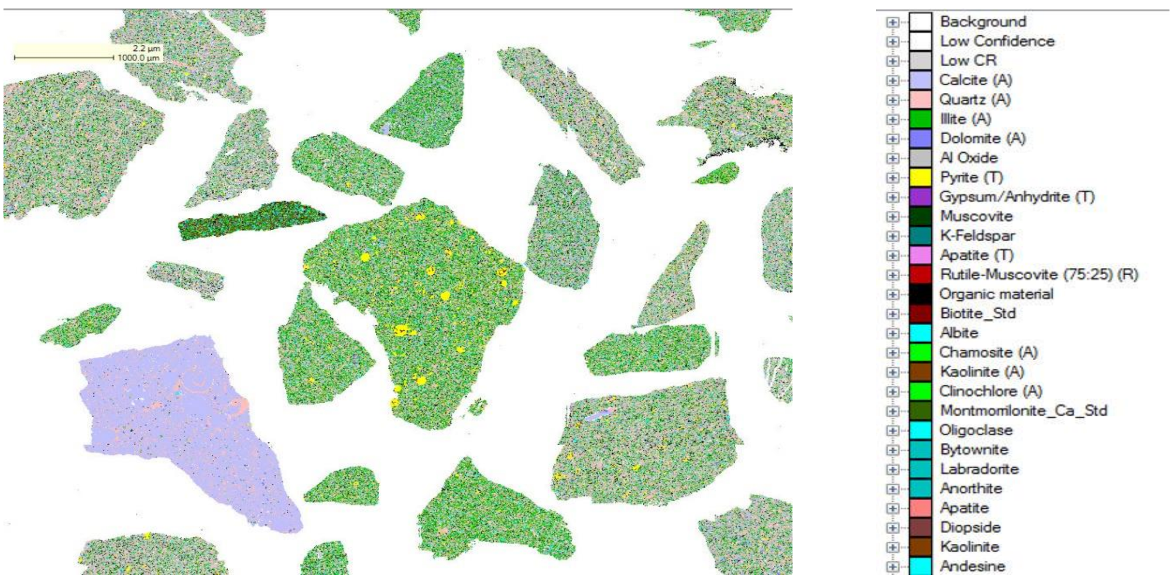


Figure 3-31 -- QEMScan false color image of cuttings from near the end of the south lateral (sample SWC-144)

The QEMScan analytical results are shown in Table 3-8.

Table 3-8 -- QEMScan analytical results for Inflection well samples

SWC-147			SWC-139			SWC-144	
Quartz	41.82		Quartz	47.31		Illite	26.67
Illite	38.39		Illite	18.82		Others	24.09
Background	14.93		Others	12.49		Quartz	22.04
Unclassified	7.44		Background	7.01		Background	9.63
Muscovite	3.16		Unclassified	4.89		Calcite	7.00
Plagioclase	3.11		Calcite	4.44		Unclassified	6.59
Calcite	1.83		Plagioclase	3.40		Pyrite	3.56
Pyrite	1.09		Dolomite	2.48		Plagioclase	3.43
Kaolinite	1.00		Muscovite	2.14		Muscovite	2.72
Chlorite	0.87		Pyrite	2.07		Dolomite	1.28
Montmorillonite	0.36		Montmorillonite	0.57		Chlorite	0.87
Rutile	0.34		Chlorite	0.44		Kaolinite	0.76
Dolomite	0.28		Kaolinite	0.38		Montmorillonite	0.37
Pyrophyllite	0.09		Apatite	0.24		Rutile	0.28
Apatite	0.06		Rutile	0.22		Pyrphyllite	0.10
Biotite	0.05		Pyrophyllite	0.07		Apatite	0.09
Others	0.04		Biotite	0.03		Biotite	0.08
Barite	0.03		Paragonite	0.01		Barite	0.03
Siderite	0.02		Zoisite	0.01		Zoisite	0.02
K-Feldspar	0.01		K-Feldspar	0.01		Siderite	0.01
Zoisite	0.01		Titanite	0.01		Paragonite	0.01
Paragonite	0.01		Zircon	0.00		K-Feldspar	0.01
Zircon	0.01		Siderite	0.00		Zircon	0.01
Glauconite	0.00		Barite	0.00		Titanite	0.01
Titanite	0.00		Glauconite			Glauconite	0.00
Epidote	0.00					Epitote	0.00
						Ankerite	0.00

While all 3 samples are from the high-gamma-ray zone near the base of the Marcellus the QEMScan images show that samples SWC-147 (north) and SWC-139 (center) are much more rich in very fine-grained quartz than the sample SWC-144 (south). The fragments of sample SWC-144 (south) are clearly more heterogeneous than those of SWC-147 (north), with some of the SWC-144 (south) fragments having similar amounts of fine-grained quartz but others having less quartz; it is in these quartz-poor fragments that most of the pyrite is found.

The relatively clay-poor composition of sample SWC-139 (center) can also be seen in the pyrolysis data in Table 3-9.

Table 3-9 -- Pyrolysis data for Inflection well samples

SWC-147 (north)			**SWC-139 (center)**			**SWC-144 (south)**	
TOC%	3.47		TOC%	7.20		TOC%	6.16
S1	5.07		S1	0.14		S1	8.50
S2	2.42		S2	0.47		S2	3.84
S3	0.32		S3	0.47		S3	0.41
Tmax	415		Tmax	362		Tmax	400
HI	70		HI	7		HI	62
OI	9		OI	6		OI	7

The quartz-rich nature of sample SWC-139 (center) is evident in the low S1, S2 and S3 values, despite having a high calculated TOC%.

Near the end of the project, vitrinite reflectance (R_o%) was determined on these three samples.

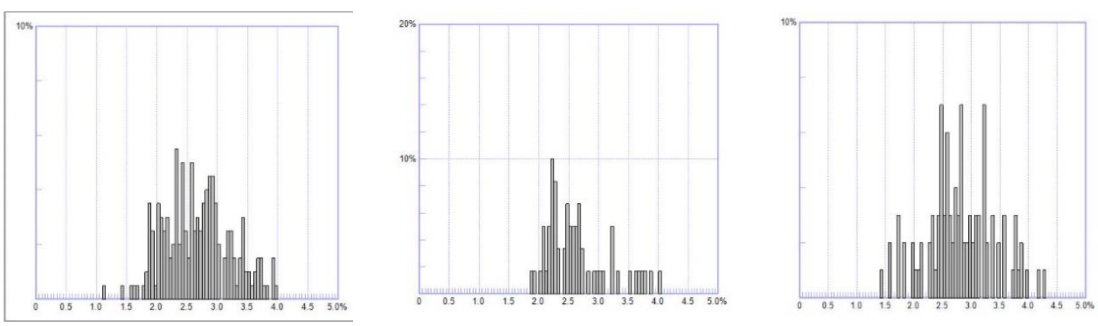


Figure 3-32 -- Vitrinite reflectance measurements on samples SWC-147 (north, left), SWC-139 (center) and SWC-144 (south, right)

It was possible to measure the vitrinite reflectance from the Marcellus interval in a test well (Erb) drilled for research purposes by The Pennsylvania State University in about 2010, sample SWC-132. This was to test the hypothesis that the Appalachian Front has a significant bearing on the gas in the Marcellus formation. This test well is 35 km south of the Hamilton pad, and thus clearly on the other side of the Appalachian Front and well within the Valley and Ridge province. Like the samples from the Hamilton wells, the sample SWC-132 is also from the top of the Lower Marcellus, just where the gamma-ray log rapidly increases. Vitrinite reflectance for this sample is about 2.2%R_o, noticeably lower than for the Hamilton wells, but still clearly within the 'gas window' of organic maturity.

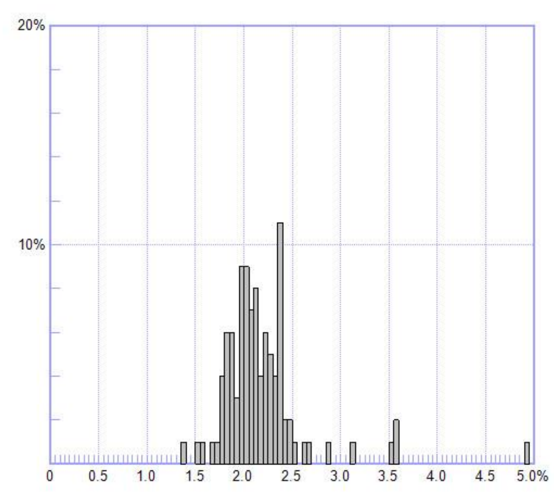


Figure 3-33 -- Vitrinite reflectance measurements on sample SWC-132 (Erg well)

The vitrinite reflectance values show an increase in thermal maturity from north to south within the Hamilton well samples, but the well even further to the south has a lower reflectance. The most likely explanation is that slight changes in lithology (c.f. Kohl, 2012) are determinate.

Finally, it should be noted that the two Inflection gas wells are considered 'good' wells. Production from them is shown in figure 3-34.

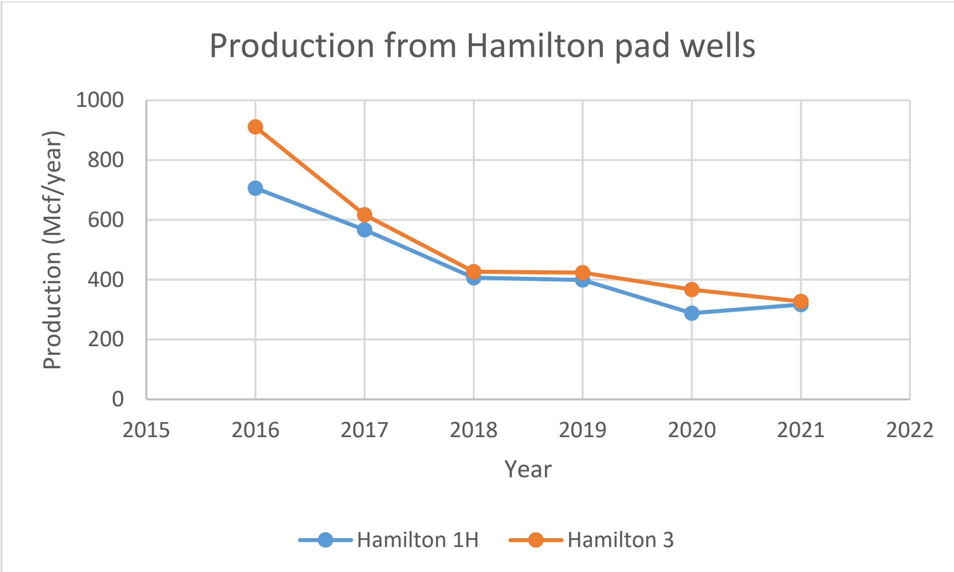


Figure 3-34 -- Production from Hamilton pad wells (Inflection Production Co.)

Since 2016 each well has been averaging more than 1,000 Mcf/day, and declines have stabilized.

Interpretation of Marcellus samples

The analytic results of the samples collected for this study confirmed the extensive previous work on the Marcellus shale. In particular, the highest organic content is at the base of the formation, but the surface samples collected did not show any regional trends with respect to mineral composition, organic richness nor thermal maturity. The two more specific studies confirmed that internal decollements exist which decrease the ability of the rock to retain methane, and that the Appalachian Front marks a change in character of the underlying shale.

Chapter 4 -- Finite resource economics

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Peak Oil

The image of the earth taken from space, seen in figure 4-1, underscores that all earth

Figure 4-4-1-- Earth from space -- the “blue marble” (NASA 1972)

resources are finite. But even before the NASA photos this was realized by numerous thoughtful researchers. In particular, because energy, not money, is what flows through all economic processes, the availability of energy resources has been an issue.

Predictions of oil supply

In particular, the.history of the oil industry is one of gluts followed by concerns over future supply. Major oil discoveries have tended to flood the market with supplies far in excess of demand. But the resulting low prices increase demand, and as the oil stops gushing out of the wells there is concern about shortages. By the end of the 19th century the Standard Oil Trust was relatively successful in smoothing out these cycles. But with the breakup of trusts in the early 20th century, the problem re-appeared. With the increasing importance of oil the role of price maintenance shifted to some extent to governments. But when output from the new discoveries began to decline, as it always did, the concern turned to what would happen when the oil ran out. In 1919 the Chief Geologist of the US Geological Survey predicted that peak oil production would occur within 3 years (White, 1919)[7]. These ups and downs of the oil industry make for exciting reading, complete with colorful personalities. Anthony Sampson's *The Seven Sisters* (1972) and Yergin's *The Prize* (1992) are good examples. In the oil fields the reality was that discoveries outpaced the rapidly increasing demand, although the path wasn't even.

Hubbert's predictions of oil supply

As new oil province followed new oil province allaying fears of shortages, and just as the vast oil resources of Saudi Arabia were becoming evident, the geologist M. King Hubbert (1956) predicted that this would all end -- and soon. Hubbert's presentation to an industry conference (Hubbert, 1956), made the bold prediction that the onshore production in the USA (excluding Alaska) would peak in about 1970. That was only 14 years away, the short time being a consequence of the exponential growth in consumption that was still occurring. That US onshore production did peak in 1970 has given Hubbert the honor of inventing the "peak oil" concept.

Hubbert's major point in 1956 was that exponential growth means that the exhaustion of a finite resource will come with surprising speed. If production grows at 7.9% per year, the absolute amount produced doubles in less than 9 years. The title of Hubbert's 1956 paper is *Nuclear Energy and the Fossil Fuels*, and his major point was that to ensure sufficient energy it was none too soon to begin a rapid transition to uranium and nuclear energy.

The concept of a peak comes from Hubbert's theoretical model of any finite resource exploitation, as shown in figure 4-2

[7] as quoted in Ahlbrandt (2012)

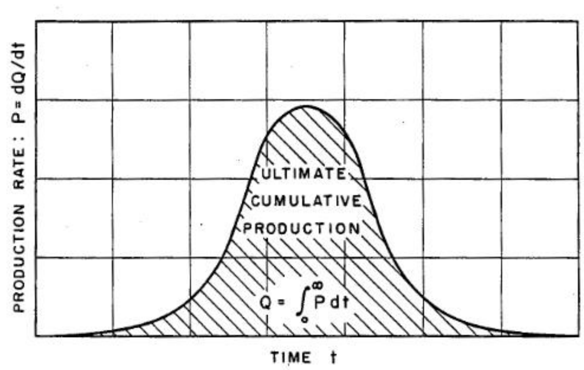

Figure II – Mathematical relations involved in the complete cycle of production of any exhaustible resource.

Figure 4-4-2 -- Production of a finite resource (Hubbert, 1956)

The popularity of the term “peak oil” is more recent, probably dating to press reports about the founding of an Association for the Study of Peak Oil in 2002[8].

Hubbert had long been interested in the finite nature of earth’s resources[9], and his first paper on the finite nature of oil is from 1938 (Hubbert, 1938). In addition to his 1956 prediction of the US peak oil production in about 1970, he predicted that world peak oil production would occur in about 2000. Hubbert’s 1956 publication predicted the year of peak production; but to make this prediction he used estimates for the total amount of oil that would be produced. In his 1956 paper he used estimates for this Total Recoverable Resource that had been made by others[10] and showed how producing that quantity of oil given the production history to date necessitated reaching a peak in production sooner than people might expect.

Hubbert continued to work on the problem of oil supply, and his subsequent papers (Hubbert, 1962, 1967, 1969, 1974, 1982, amongst others) used a variety of techniques to estimate both the ultimately recoverable resources and the approximate date for the peak in production. Perhaps the most important insight was his realization that oil must be discovered before it is produced and hence the information from discoveries can also point to the total amount of oil before the production information provides the same result.

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[8] See Aleklett (2012) p. 10 for a history of the term.
[9] Kuykendall (2005) has compiled a bibliography of Hubbert’s publications. See http://www.hubbertpeak.com/hubbert/bibliography.htm (accessed 2014-09-02)
[10] Notably those of Lewis Weeks, chief geologist of Standard Oil of New Jersey (now ExxonMobil).

Dr. Hubbert was a brilliant scientist. A recent biography (Inman, 2016) chronicles much of the development of his thinking about oil and other natural resources and details the dissention that Hubbert's ideas caused within the industry and within the US Government. One of Hubbert's greatest strengths was to simply plot the data and present it with what, to him, were obvious conclusions – and then not back down in the face of political pressure. This didn't make him popular in many circles, but he had the good luck to have supportive employers for most of his career. And, as he would point out, he was only collecting data and presenting it – if anyone could show that his data was incorrect or that his reasoning was faulty he would retract his opinion. This seldom happened, although he was as critical of his own work as he was of the work of others.

Hubbert's predictive insight, as he put it, was that when the last drop of oil is produced, the amount produced will be equal to the amount discovered (Hubbert, 1962). Using this insight, Hubbert was able to make his own projections for the total amount of oil available from published data on discoveries, rather than relying on estimates from others as he had done in 1956. He then proceeded as before to use this total resource number to predict when the peak production rate would occur. Although Hubbert continued to explore the topic, the essence of his theory was in place by 1962. This did not please the political and business powers within the oil industry who continued to proclaim that there would always be enough oil; that if oil became scarce the price would go up which would result in more drilling and more oil being discovered. So little was done to address the concerns that Hubbert raised.

A younger colleague of Hubbert's, Ken Deffeyes, dug through Hubbert's mathematics and published Hubbert's technique in two books (Deffeyes, 2001, 2005). In addition, Deffeyes validates some of Hubbert's work by examining the oil discovered in Kansas[11], which is important because it ties Hubbert's methodology to statistical sampling. Using Hubbert's logistic assumption with known production data, Deffeyes was able to make new global

[11] Kansas has been very thoroughly explored for oil. This allows statistical forecasting methods to be tested against known results.

projections: ultimate recovery of 2,000 x 10^9 barrels with a peak production date of 24 November 2005[12].

It is important to note that Hubbert and Deffeyes are using statistical methods to reach their results. Statistical methods are used frequently in science. Deffeyes noted a saying amongst statisticians “you don’t need to eat the entire ox to know that the meat is tough”.

Many in the oil industry found, and continue to find, Hubbert’s forecast unsettling. The intellectual excitement for the exploration part of the oil business was, and continues to be, figuring out new places to drill for oil. While exploration or “wildcat” wells have a low success rate, the successes can be spectacular when they come. Most people in the industry will acknowledge that, given that the earth is finite, a peak must exist. But they question its timing, the total amount of oil that will be produced, the shape of the production curve, and other aspects. Very simply, if the total amount to find is larger, the peak date can be farther in the future. So many, perhaps most, industry analysts have argued that the ultimate recovery figure is larger than Hubbert’s or Deffeyes’ calculations. Many of the arguments date back to the 1960s in the wake of Hubbert’s paper, and are still being used today. The range of a number of oil estimates is shown in figure 4-3

[12] Deffeyes states that the uncertainty in the analysis is ±1 month, allowing him to choose, with humor, US Thanksgiving Day of 2005 as the actual date of peak oil (Deffeyes, 2005, p. 43).

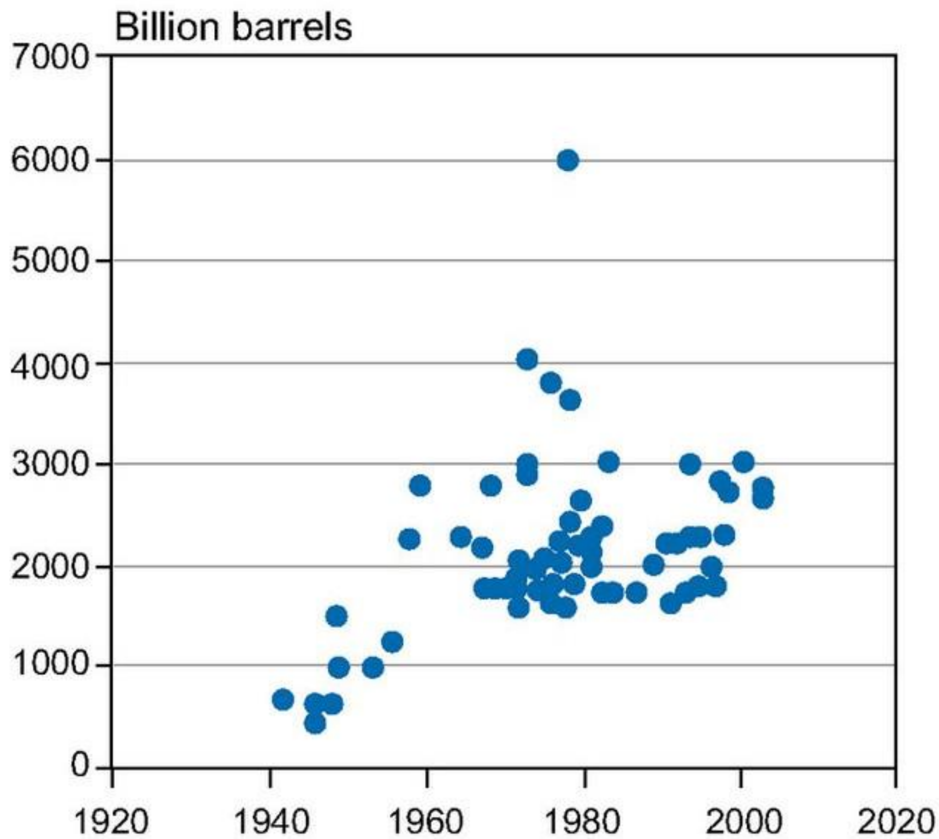


Figure 4-4-3-- Estimates of Ultimately recoverable oil (from Sims et al., 2007)

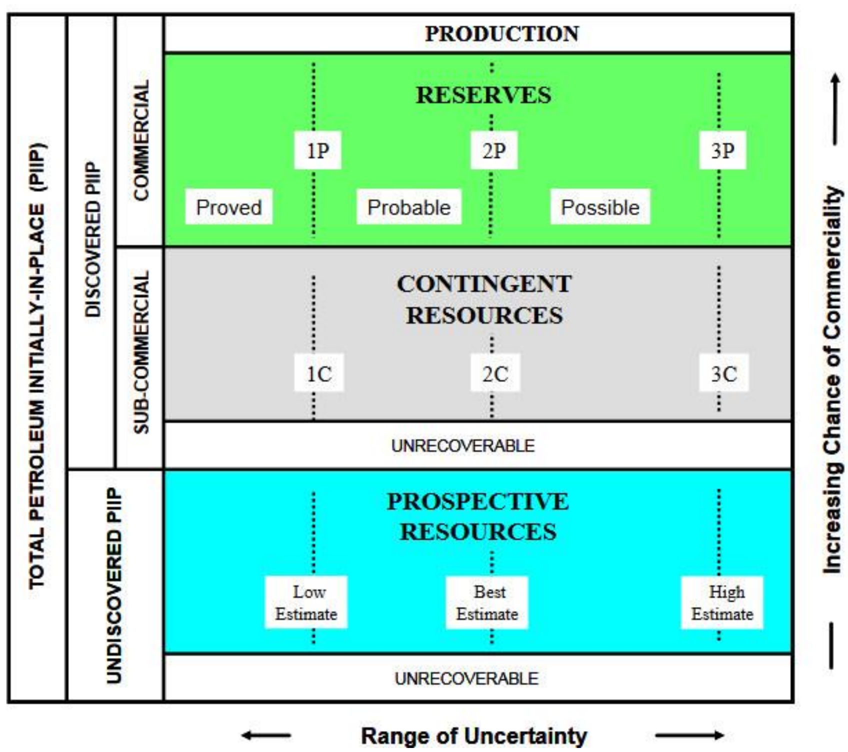
The 1970s saw a more widespread acceptance of Hubbert's thesis, although many in the oil industry remained sceptical[13]. Numerous other forecasting techniques were used, for example calculating the amount of oil drilled per foot of exploration wells drilled, or doing volumetric calculations of entire basins. In addition to the debate surrounding any new insight, Hubbert's papers created a stir because of their timing. NASA's first photographs of "Spaceship Earth" (figure 4-1), the Club of Rome's *Limits to Growth* (Meadows et al., 1972) report, and gasoline lines resulting from the Arab embargo all combined to create a sense that Hubbert's theory had merit. Then, when the price of oil fell in the mid-1980s so that there was more than ample supply, there seemed to be plenty of oil available and interest waned in projecting when this finite resource would run out.

[13] A conference in 1974 (for proceedings see Haun (ed), 1975) was held at Stanford University on the subject of 'Methods of Estimating the Volume of Undiscovered Oil and Gas Resources'. Hubbert was conspicuous by his absence.

Discussions of peak oil, and of the policy question “are our oil supplies adequate?”, often come apart over the differences and relations among the terms resources, reserves, and rates of production. One might call these the “three Rs” of oil policy.

The oil and gas industry has adopted a common vocabulary to describe the various types of oil and gas which the various companies, based on their specific surveys, think is in the ground. Because oil and gas is found in rocks thousands of feet below the land surface, calculations of how much is there are subject to many types of uncertainty. In Table 4.1, which is the industry standard, this type of technical uncertainty is expressed on the horizontal axis. We have seen that the amount that may be economic to produce will depend on many factors, any of which may change. This is incorporated in the vertical axis together other uncertainties. The total oil or gas that was originally in the rocks is the area of the table. The amount produced so far is known, so that is the solid white bar across the top. After that are the important definitions.

Table 4-1 -- Oil and gas Industry definitions of reserves and resources (SPE, 2011)



Reserves are oil or gas that has been discovered and evaluated as being economic to produce (“commercial”) based on wells having been drilled. In conjunction with the detailed seismic surveys that have been done around the well, the likelihood of a well producing more oil can be calculated. The technical uncertainty in the evaluation increases with the distance from the tested well and with many other specific factors. Taken together, the amount of oil or gas for this known accumulation can be divided into proved (>90% certainty), probable (between 50% and 90% certainty), and possible (less than 50% certainty reserves.

Resources is a more encompassing term. The SPE guidelines consider resources as being distinct from reserves, as shown in Table 4-1. Unfortunately, the word is frequently used collectively to include reserves as well. The agreed SPE definition is that resources do not include reserves. Resources are divided into two categories: contingent and prospective. The contingent resources are reasonably well known, usually as the result of drilling; it is just that at the current price of oil or gas they are not economic and are therefore not worth developing. The line dividing reserves and contingent resources can easily move up and down – indeed, it frequently does as the price of oil and gas fluctuate. Note that there is no such thing as a "contingent reserve".

The Ultimately Recoverable Resources (URR) sometimes discussed is the same as the SPE's Total Petroleum Initially In Place (PIIP), and Remaining Recoverable Resources is the URR minus the production to date.

In addition to calculations based on flow tests from wells, interpretation of seismic surveys of the discovery area, and other such technical criteria, these evaluations also consider the existence of infrastructure to bring the oil or gas to market and the legal ownership status of the oil or gas. The SEC[14] allows publically traded companies to show Proved Reserves as an asset on their balance sheets, but nothing else. Accounting rules are thus important in the definition and valuation of what is shown as Proved Reserves[15].

[14] The SEC (Securities and Exchange Commission) is the US government's agency that regulates financial transactions.

[15] See Financial Standards Accounting Board ASU 2010-03 (FASB, 2010)

Rate of production is what it purports to be, the rate at which oil or gas is produced. But dividing reserves by the rate of production doesn't usually give the time remaining before the file stops producing. The rate of production declines with time; hence a field that has 10 million barrels of oil reserves producing at 1 million barrels per year will not produce for 10 years and then just stop. Rather, the rate will decrease day by day and it may take 20 years or more before the last of the 10 million barrels is produced, sold, and the field declared uneconomic.

Just as Hubbert developed his theory during a time when oil was plentiful, so in the 1990s two geologists, with oil again plentiful, warned that oil would run out sooner than many expected. Publishing in the popular science magazine *Scientific American*, Colin Campbell and Jean Laherrère (1998) pointed out that oil production would soon begin to decline. The popularity of the specific term "peak oil" is more recent, probably dating to press reports about the founding of an Association for the Study of Peak Oil in 2002[16] by, amongst others, Colin Campbell.

Campbell's predictions of oil supply

While Hubbert's projections were founded in statistics, there are other ways to make a similar estimate. One of these is to use a data-intensive study to project oil well and oil field production declines. When an oil field is first discovered the next step is to drill additional wells to find out its extent. As additional wells are drilled the production from the field will increase. But eventually the areal limits of the field are reached, the volume of the reservoir can be calculated with increasing accuracy, and the oil is produced. As the oil is produced, the output from individual wells declines over time; the total output from the field, which is just the sum of all the wells, also declines. Every field is different, and such declines for a field may not start for a number of years as new wells are drilled to bring all areas of the field into production. Once declines start they may be slow and steady, or they may be precipitous. To some extent, the rate at which a well is allowed to flow determines the amount of oil that can eventually be produced from it, so production engineering makes a difference in the amount of oil produced. Periodically, it may be worthwhile to add new production technology, creating an upward step in the decline curve. In the 1990s, international exploration geologist Colin Campbell, working

[16] See Aleklett (2012) p. 10 for a history of the term.

with a large, proprietary database[17], summed up these patterns for all the world's oil fields. Campbell (1997) concluded that global oil production was about to become seriously constrained. This was the methodology which Campbell and Laherrère used in the *Scientific American* paper; their basic message was that as these declines set in on a global scale it wouldn't be possible to reverse the trend by either new technology or new discoveries. That their total figures from a different methodology were similar to Hubbert's final predictions in 1982 lent credence to both approaches. Campbell (2013) has since published a detailed atlas of this work.

In the rest of this chapter the Hubbert approach, which uses global data to make predictions, will be referred to as a 'top-down' approach; Campbell's summing up of thousands of individual fields methodology will be referred to as a 'bottom-up' approach.

All theories have some underlying assumptions, and peak oil is no exception. Hubbert's use of a logistic curve to model oil production is one such assumption. Hubbert himself discussed the possibility of more than one peak. Hubbert never clearly explained his decision to use a logistic curve. Deffeyes (2001), who knew Hubbert personally, opines that it was partly a lucky guess that seemed to work. Whatever the reason for choosing a logistic curve, the mathematical transformation to a linear plot allows calculation of the final amount that will be recovered when the last barrel is produced; Hubbert and many others concluded that this final number for oil is about 2 trillion barrels (2×10^{12} barrels). From that number, a knowledge of known production to date and symmetry the peak can be found. Deffeyes (2005) gives the date for this peak as being in November, 2005. The fact that production has increased since that date is clear evidence that the theory needs some modification, but why and to what extent remains hotly debated. In contrast, Hallock et al. (2014) show good agreement with a Hubbert analysis for many countries. Bentley (2002, 2009, 2016) gives a detailed analysis of the problems.

[17] Petroconsultants collected and compiled data from the exploration and production sector of the oil industry for much of the world, and then sold the compilations back to the oil companies. The company has since been acquired by IHS, which continues the activity.

Despite some caveats in some of Hubbert's later papers, the symmetric form of Hubbert's curve has continued to influence the discussion. While there were and are many critics of the total resource figure, which is the area under the curve, and the date of the peak, the shape of the curve after the peak has received less attention. The logistic curve's symmetry suggests that just as the economy has phased into oil, it will phase itself out of oil without major economic upheavals. Thus the use of logistic curve has, perhaps ironically, worked to lull concerns given that it shows a gradual replacement of oil energy rather than a crisis.

Supply peaks vs. demand peaks

The gentle decline in production argues for a "demand peak" rather than a "supply peak". Hubbert, and most other geologists and oil industry analysts, start with a focus on the oil that is in the ground. Since this must be limited, their peak production is constrained by the supply of oil – it is a "supply peak". But the peak could be caused by some better, cheaper replacement for oil lowering demand. This is a "demand peak". One example of a demand peak is the production of anthracite coal in Pennsylvania (Carmalt and St. John, 1986), as shown in figure 4-4

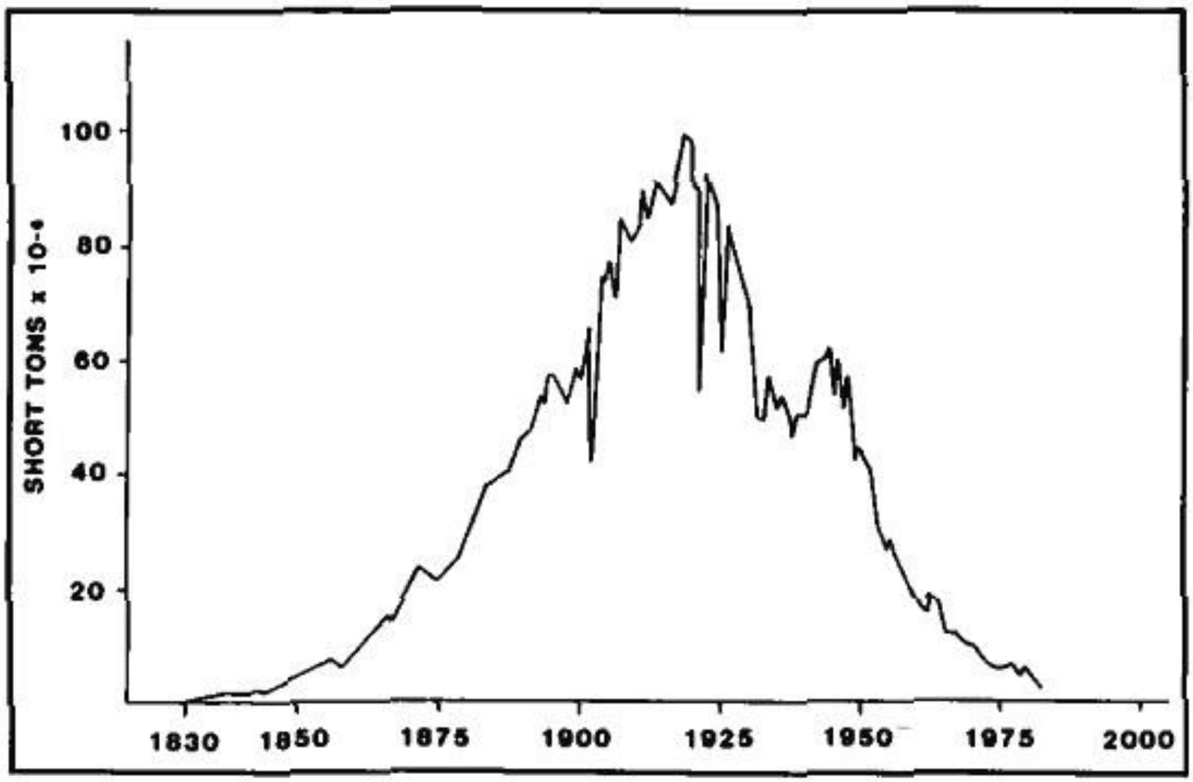


Figure 4-4-4 -- Anthracite coal production in Pennsylvania (after Pyros, 1979)

Pennsylvania has not run out of anthracite coal; rather the cost of bituminous coal is so much lower that it is no longer profitable to mine anthracite except for small amounts that can be sold for premium prices. Economists generally like the demand peak approach, because it fits well with neoclassical economic theory. Those arguing for an oil demand peak say that oil will be replaced by some alternative energy when the alternative energy becomes less expensive; this will lead to the demand for oil dropping. The reason for some alternative energy becoming less expensive is presumed to be due to improvements in technology. It doesn't matter whether the alternative energy is another fossil fuel such as natural gas or some renewable energy technology. Given the ubiquitous-ness and importance of oil , and the magnitude of its use, it's a bit hard to conjure up a replacement

Definitions in the peak oil analysis

Both the top-down and the bottom-up approaches have had to contend with the fact that oil production has not clearly peaked[18]. Those who believe that an oil peak will be caused by supply limitations tend to argue that the reason is that "unconventional" sources such as tight oil and tar sands and even natural gas liquids have been added to the oil production statistics. By this standard, peak oil has been reached for the conventional oil fields that Hubbert analyzed and the question becomes a narrower one of how long the rates of such unconventional production can compensate for the decline in conventional production. This has more impact on the bottom-up analysis than on the top-down analysis. In the bottom-up approach, one is always limited by the current state of the technology. By contrast, the top-down approach uses trends from historic data which have seen technologic improvement since the first wells were drilled in the 19th century; hence the top-down projections into the future contain at least some embedded presumption of technological improvements. Foreseeing some of this, Hubbert mentioned the tar sands and oil shales in his papers, but there wasn't any production from either of them when he was writing, so his statistics and resource estimates don't include them. Tight oil reservoirs were also known, but any oil they contained was not included in reserves because until recently it was not thought that such low permeability reservoirs would ever be economic. Nevertheless, the result of adding tar sand production, which requires processing to become oil, to the oil production statistics does beg the question as to whether the data underlying the analyses are consistent. As mentioned earlier, oil shale is not presently being produced.

In addition to tight oil and tar sands, the unconventional label is frequently used to include offshore prospects in more than 500 meters of water and prospects in the Arctic, particularly offshore in the Arctic Ocean. To date the Antarctic treaty, which prohibits commercial exploitation of that continent, has not been challenged. But if oil production peaks from non-Antarctic sources don't bet that this treaty won't be challenged before much longer. Unlike tight oil and gas (especially shale oil and gas), tar sands, and oil shale, such prospects are

[18] At least it hadn't as of the end of 2021.

unconventional only in the sense that they are pushing the limits of existing technologies, not in the sense that they are tapping a different sort of oil deposit. Exploration that occurs in these areas is traditional – the companies look for a good source rock which has reached “oil window” temperatures and from which the oil has then migrated into a porous reservoir where it is trapped.

Another source of additional oil from improving technology is by enhancing the percentage extracted from in the reservoirs that are being produced today. Petroleum engineers know that the reserves for almost every field increase as time goes on. There are several reasons for this. First, the P1 reserves, which are the ones that can be listed as assets on a balance sheet, are necessarily conservatively calculated. Because they are assets they can be used as security for bank loans, and banks want to make sure of getting their money back. Frequently the bank will use lower price projections than the oil company to calculate the amount of security being proffered by the oil company. So the reserves shown are conservatively stated, and as the field produces, this figure can be revised upwards. Second, all the oil doesn’t all come out of the rock. Depending on the rock’s physical characteristics, only a fraction will flow into the well to be produced. As this natural flow declines, the company will use different techniques to coax more oil out from the rock. Such techniques are collectively known as Enhanced Oil Recovery (EOR) methods.

There are many of these methods, but many involve using some wells to pump something down into the reservoir. As this fluid enters the reservoir rock, it will push the oil in front of it into the producing well. Frequently this physical push will be combined with something that makes the oil flow more easily, for example steam, or a chemical that will mix with the oil and help it to flow to the producing well. These enhanced methods can follow one another during the course of producing a field and are thus called secondary recovery or tertiary recovery. But it is difficult to get 100% of the oil in a reservoir out; recovery can range from 20% of the oil originally in place in the reservoir to over 50%. The average is some 36 percent, and enhanced recovery adds only a few percentages at a rather high price

Two comments about these enhancement technologies: first is that they cost money. Each such project will go through an approval process similar to the project financing analysis used for the original well(s). The cost of drilling the injection wells, the costs of whatever is pumped into them, the possible cost of separating oil from this material when it shows up in the producing well, the time-series price of all of these materials and the price of oil over the project life all have to be worked out. This enhancement project will be another possible use of the company's capital and so it will be compared to other possible projects. The second is that it is unclear how much the additional production changes either Hubbert's top-down, or Campbell's bottom-up approaches used in forecasting peak oil. For the statistical approach, water was being used for secondary recovery in the Bradford giant oil field in Pennsylvania starting in the 1890s. For the bottom-up approach, secondary and tertiary recovery programs are the norm in the industry today, so the projections that Campbell and Laherrère use have included this recovery.

More fundamentally, the assumptions behind the peak oil projections are what an engineer would term the "boundary conditions" for the theory. All the conventional analyses presume the migration from a source rock into a porous reservoir rock from which the oil is produced by traditional means. Tar sands, which are mined (and which Hubbert mentions in his papers, but not in his analysis) don't fit these conditions. Shale oil and gas don't fit these conditions; other tight plays are more similar to traditional plays but at the very lowest limits for permeability of traditional fields, and hence are at the limits of the boundary conditions. The result is that the projections based on any of the peak oil methodologies are likely to diverge from actual data. Indeed, this is the reason that production since about 2005 has not followed the peak oil projections.

As mentioned above in discussing demand-side peaks, economists have generally been scornful of peak oil theories. As Bardi (2013) has pointed out, the debate between those who see depletion as an urgent, near-term issue and those who are sure that the combination of technology and human ingenuity make depletion a problem only in the distant future has been going on for well over a century. One of the first to consider the issue was the economist

William Stanley Jevons in his classic work *The Coal Question* (1865), which considered what is essentially the same problem of resource availability for England's coal resources. Jevons was also an astute economist; he observed not only that the amount of coal had to be finite, but that the more that was mined, the more expensive the coal became. When he considered using coal more efficiently he noted "Jevon's paradox"[19]. Basically the paradox is that using coal more efficiently does not reduce the amount of coal used; one might think that the more efficient use would result in less coal being needed, but in practice the use of coal increases because the more efficient use of coal effectively lowers its cost when measured per unit of energy. With the lower energy cost, demand increases, cancelling out the efficiency savings. Jevons was able to demonstrate this with respect to coal in 19th century England. Modern environmentalists know this as the 'rebound effect' and have observed it in modern situations (Knittel, 2011).

The reason that economists like the demand-side explanation for peak oil is that it better fits their economic framework. If there is a shortage, the price will rise and more of the material will be produced. Brian Skinner (1986) provides a good review of how this works in the mining industry. The late Morris Adelman, an MIT economics professor, is as strongly identified with the position that increasing demand will bring forth increasing supply (Adelman, 1993) as Hubbert is with the postion that there are geologic limits to the amount of oil. This approach can be seen in the work of the US Geological Survey. The USGS is a respected scientific organization which is apolitical and was established "...to examine the geological structure, mineral resources, and products of the national domain" (Rabbit, 2000). In 2000 the survey published an extensive assessment of world petroleum resources, arriving at a final estimate of 3 x 10^{12} barrels of likely recoverable oil, or about half again as much as most of the peak oil estimates (USGS, 2000). One of the key concepts in the USGS methodology is that of the "resource pyramid", as described by McCabe (1998) and shown in figure 4-5.

[19] See Owen (2010) for a precis with commentary of Jevon's paradox.

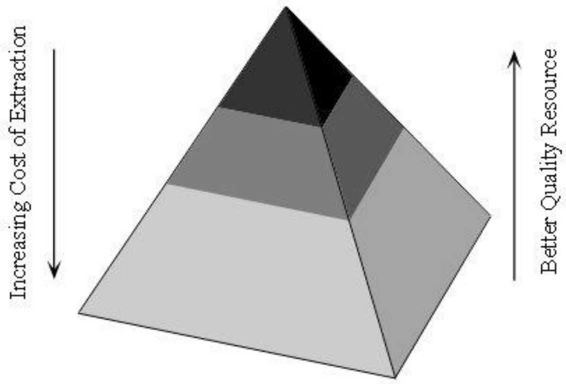


Figure 4-4-5 -- Resource pyramid (after McCabe, 1998)

The concept behind the pyramid is that at any given time, the combination of price and technology can be represented by a horizontal plane through the pyramid. Above the plane lie the currently economic resources, and below the plane lie those that are uneconomic. Hence as oil becomes more scarce, the price rises and the plane moves to a lower level. This will make a much greater part of the resource available as Adelman predicts.

The pyramid approach to a finite resource is similar to that of decreasing ore grades known from mining. Skinner (1976) has argued that for some metals, the distribution of the metal in the earth's crust is bi-modal. For example, lead can be found dispersed in granite, but the amount of lead is so small, just 0.0039% in an average granite, that it would not be economic to mine granite in order to obtain lead. Rather, one looks for special geological situations in which lead forms the mineral galena (PbS), which may comprise in the neighborhood of 10% of the rock in a lead mine. It is this concentration of lead molecules into a mineral that makes an ore, and hence a lead mine.

Both the bottom-up and the top-down oil methodologies agree that most of the oil reserves, at least to date, are found in giant oil fields. Giants are fields that have more than 500 million barrels of recoverable oil. The most recent compilation (Horn, 2011) indicates that approximately three-quarters of the projected global resource is contained in the giant oil fields. Perhaps the giant fields should be viewed as similar to ore minerals, and hydrocarbons further down the pyramid should be considered more like the lead distributed in a granite. But unlike the disbursed lead in granite, some of the disbursed hydrocarbons – notably the tight oil deposits like the Bakken and the tar sands – are marginally economic at present.

Thus many in the oil industry do not see any immediate constraint on oil supplies, even if the conventional peak oil is behind us. For example, the IEA (Tanaka, 2009) suggested that the total amount of oil available to the world economy at prices which are within reach of affordability is vast.

Two things are clear. First is that definitional problems abound. While the BP series showing reserves shows an increase from year to year, the details in the data show that Canada increased its oil reserves almost 4-fold from 1998 to 1999 as the result of a decision to include the tar sands in the numbers; similarly, inclusion of the Orinoco tar sands in Venezuela's reserves resulted in that country showing an almost 2-fold increase from 2007 to 2008. In both cases the resources were well known for many years before they were considered in the reserve numbers and the inclusion was not due simply to resources moving from the resource to the reserve category. Second is that across all countries, the higher oil prices of the 21st century (until 2014) led to a transformation of resources into reserves.

Since Hubbert's original 1956 paper the two things that everyone wants to know are: how much oil is there? and when will it be impossible for oil production to increase? The debate that Hubbert joined in 1956 continues today. In BP's annual statistical tables (now published by the Energy Institute), only the years 2015, 2019 and 2020 show an actual decrease in reserves (figure 4-6), that is years in which production exceeded new discoveries. But it won't be clear for several more years whether the global economy has reached "peak oil".

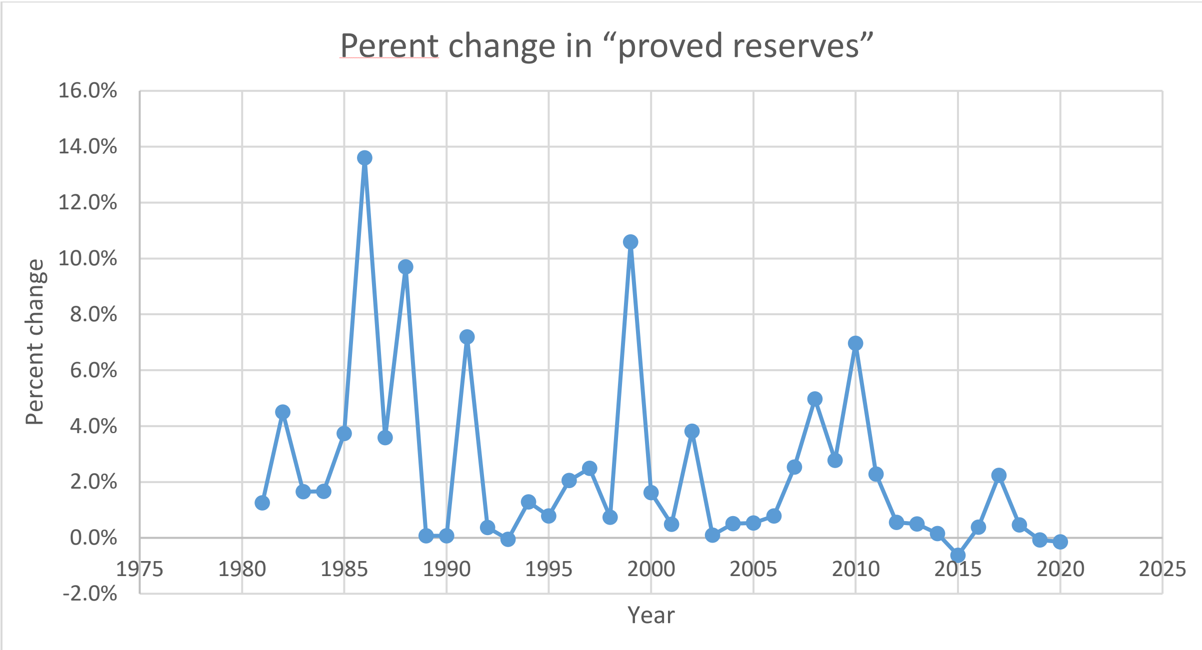


Figure 4-6 -- Percentage change in proved reserves (data source: BP and Energy Institute statistice)

There are a number of important points which are generally overlooked. The first is that, even if current oil production is at about its eventual peak there are considerable additional resources which, because they are presently uneconomic, can be utilized should supply constraints lead to higher prices. What isn't so clear is whether the needed investment is being made to use such resources over the intermediate term, and how to address the long-term problem that exponential growth cannot ever be supplied with a resource which does not grow exponentially – and no finite resource can grow exponentially. That was Hubbert's original point, and it is still entirely valid.

So is there a resolution to the question of whether we have reached peak oil in 2024? Not really. In addition to an oil price driven only by supply and demand, there are other factors, particularly political and environmental issues involved. Resulting higher prices result in very expensive oil (low EROI values), which tends to indicate that the peak of traditional production has been reached.

Energy in the Economy

Energy isn't like other resources. Whether mined as coal, produced from wells as oil or natural gas, released in a nuclear reactor, or captured by panels or windmills, energy is consumed. More precisely the energy – which we all learned is neither created nor destroyed – is changed from a more concentrated form to a more diffuse form. The fossil fuels contain energy that has been chemically stored; when fossil fuels are burned this chemical energy is converted into heat energy.

Some basic thermodynamics

Studying the flow of energy is the science of thermodynamics, literally 'heat flow', which lies at the heart of all dynamic systems[20]. The earth, its oceans, ice caps, rivers, ecosystems, plants, animals are all dependent on flows of energy. So, too, is "the economy", which is what allows us to have a style of living so very different from our hunter-gatherer ancestors. Particularly important to the way energy, and thus oil, moves through the economy are the First and Second Laws of Thermodynamics. The First Law, also called the Law of Conservation of Energy, states that energy is neither created nor destroyed, but only is transformed from one form into another. As modern science developed in the 17th and 18th centuries, the conservation of various forms of energy became more clear. But it was not immediately obvious that the different forms of energy were all, in fact, the same physical entity. In particular, the equivalence of heat and mechanical energy was only established in the late 18th century, in part by being able to observe the conversion from one to another during the manufacture of canons.

The Second Law of thermodynamics involves entropy and states that entropy cannot decrease[21]. What is entropy? It is the amount of **unuseable** energy contained in a substance at

[20] The subject of thermodynamics is covered in very many textbooks and on-line resources. Principle references consulted for this discussion are: Gallucci (1973) and Larsen (2014).

[21] We generally learn the second law very early in life; the nursery rhyme Humpty Dumpty is one articulation of the Second Law.

a particular temperature. More simply, the Second Law says that the amount of useable energy can only decrease.

This is why we think of energy as being consumed despite the First Law stating that it isn't. When we 'use' energy, we are converting it from a usable form to an unusable form. The form which cannot be used is generally heat, which we release into the environment. If I am in a large room in which there is a cup of hot water, the hot water will cool as heat flows from the cup into the rest of the room. At the start, the heat of the water could poach an egg; after the cup of water cools it cannot. The total heat in the room has not changed, but it has dissipated into a much larger space which makes it unuseable. The energy before and after is the same (First Law), but while before there was some useable energy, after there is only unuseable energy (Second Law). Because there is more unuseable energy afterwards the entropy has increased. Within the room we cannot get that energy back to a useable form again. Because entropy can never decrease overall, it is sometimes called "time's arrow".

The example of the cup of water in a room also illustrates two additional points about thermodynamics. The first of these is that our though experiment of the hot cup of water in a room involves a flow of heat until the heat is evenly distributed in the room and no more heat flows. This is an equilibrium condition. The second point is that a system can only reach equilibrium if we have boundaries that prevent anything from entering or leaving. In the almost two centuries since the basic principles of thermodynamics were first worked out thermodynamic analysis has proved to be a robust explanation of physical and chemical processes.

When thermodynamics is considered at a molecular level, entropy is found to be associated with the amount of disorder amongst the atoms and molecules of the substance or system being studied. Saying that entropy is a measure of disorder is thus a useful, although perhaps oversimplified, way of understanding the concept of entropy. This is illustrated in figure 4-7

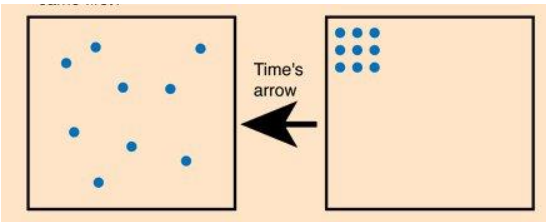


Figure 4-7 -- Ordered and disordered molecules in a box (after Nave, 2000)

Is there any way to make entropy decrease? There is, and it happens all the time. The hot cup of water is an example. How did it get hot? The short answer is that we added heat, *i.e.*, energy, to it. On analysis, everything that that we do which requires energy is creating a local area of lower entropy at the expense of increasing the entropy of another system; this local low entropy area will dissipate over time, increasing in entropy as its energy diffuses into the surroundings and becomes unuseable.

Note that our thermodynamic example of the cup of hot water in a room has a time dimension only until the water and the room are at the same temperature, that is are in equilibrium. Once at equilibrium the system is time-independent[22].

Parallel to the development of the laws of thermodynamics in the 19th century, economists were also looking at equilibrium. A foundation concept, taught in elementary economics, is that both demand and supply vary continuously with respect to both price and quantity, and these two find their equilibrium where they meet, as shown in figure 4-8. While economists consider this an equilibrium, it is actually a steady state condition.

[22] That the equilibrium will never change in our room is not quite true – over billions of years the sun's nuclear reactor will use up all its fuel and the solar system will cool down to a temperature very close to absolute zero – increasing the universe's entropy as it does so.

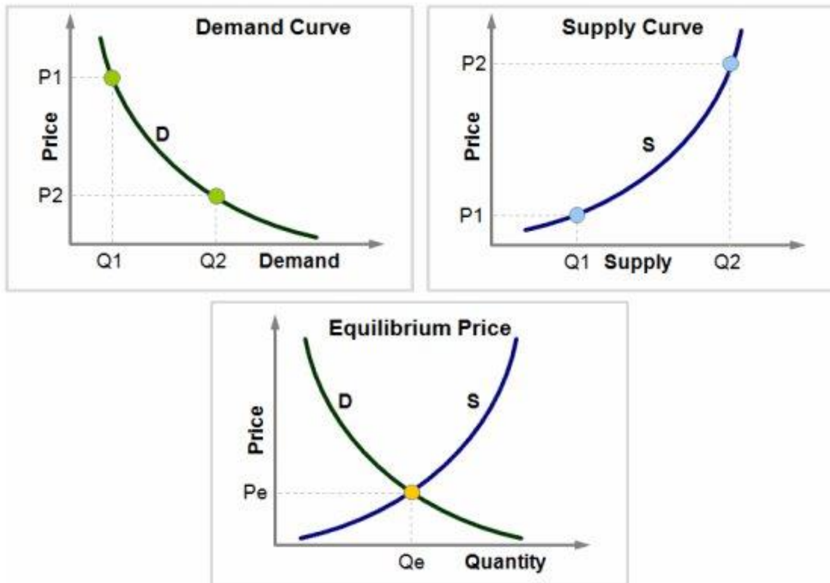


Figure 4-8 -- Demand, supply and the determination of price as the equilibrium of the two (Rodrigue, 2013)

In the latter half of the 19th century, economists developed such equilibrium models using the same mathematical tools that the physicists were using for energy equilibrium studies. Generally called "neoclassical economics" this equilibrium approach to understanding the economy has remained central to much of economic theory to the present day. Quite self-consciously the three economists[23] who, essentially independently, developed the neoclassical approach were attempting to make economics a science that was just as respected as physics. Walras (1874) was particularly keen to be able to bring the mathematical rigor of physics to economic problems (Beinhocker, 2006), although Jevons had already published his book, *A General Mathematical Theory of Political Economy,* in 1862. Whether in physics or chemistry or economics the equilibrium state is the simplest, and hence the mathematics of equilibrium are the most tractable.

But the natural world isn't in equilibrium. What may seem at first glance to be at equilibrium is generally a steady state. An analogy is the human body. An adult human may look the same day after day or even year after year, but he or she is not at equilibrium with the environment. Rather, he or she is continually processing flows of air, food (chemically stored energy) and

[23] The three were Jevons in England, Walras in France/Switzerland and Menger in Austria.

water. Similarly, an entire ecosystem is supplied with energy (primarily sunlight), nutrients and water all of which flow through the system[24]. Descriptions of equilibrium are useful because they indicate the direction in which reactions will occur but it is only a direction; in a steady state the equilibrium condition is never reached.

Energy systems

The economy is similar. It is a dynamic system which is continually processing various inputs to provide the outputs which we value and measure as GDP. When one thinks about any economic activity – mining, shipping, cooking, working, entertainment, think of anything -- a short reflection will confirm that the activity uses energy. Even the financial markets, which at first glance might appear to be devoid of an energy input, require energy. Financial markets require data which is then processed. Collecting the data takes energy, even if only small amounts of electricity to directly store a data point in a computer. In addition to the energy that is used directly there is the energy that various humans use in collecting and processing such data, and in interpretation and decision-making. In short, every economic activity requires energy.

The flow of energy through a system results in an increase in entropy. That's why we get hot and sweat when we exercise. Our bodies maintain a balance between the energy we take in and the less useable energy we return to the environment. Similarly, the earth maintains a balance between the high-grade energy that it receives from the sun and the low-grade heat energy that it re-emits into outer space. Unlike the closed, equilibrium system, the output of an open steady-state system will need just as much energy today as it did yesterday, and it will need the same amount again tomorrow. This applies to the global economy just as surely as it does to the human body or to the entire earth. If the economy is growing, it will need energy for both its steady state condition as well as additional amounts for the growth. Because of the Second Law, all of this energy use will become unavailable and there will be an increase in entropy.

[24] See Hall and Klitgaard (2012) for extensive discussion of energy flows through ecosystems.

The economist Nicholas Georgescu-Roegen understood that the economy was a steady-state rather than an equilibrium system. His 1971 book *The Entropy Law and the Economic Process* represents a completely different view of economics from that of the neoclassical or Keynesian economic models which focus on equilibrium economic states[25]. Georgescu-Roegen's view of the economic process, while still considered iconoclastic by most economists, held that value is created by irreversible thermodynamic processes, *i.e.* by processes that increase entropy. In examining the economic process from a thermodynamic perspective, Georgescu-Roegen argues that not every process that creates entropy is an economic one; rather to create economic value the process must be irreversible, create a local area of low entropy, and that the process must create something that human beings value[26].

Ecologic systems

Seeing the economy as a steady-state system rather than as an equilibrium system is a major leap in outlook for many economists. The viewpoint may be easier to grasp by analogy by looking as some of the concepts in ecological systems that have been developed over the past half-century[27]. Photosynthesis is used by plants to live; plants process inputs from substances in their environment, generally minerals from the soil and carbon in the form of carbon dioxide from the atmosphere and with energy from the sun create a low-entropy organism. We can see that the plant is a low-entropy island when it dies, because it decomposes. Herbivores eat plants, and carnivores eat herbivores, in each case the animal uses its food as a source of energy and converts this to provide maintenance of themselves as a living organism. At each point in the food chain, the consumer is a low-entropy island and maintains this low-entropy state by the energy embedded in the food eaten. Furthermore, each step of the process creates some entropy, so the total amount of energy needed increases the further up the food chain one goes. When its energy supply vanishes, the organism can no longer survive.

[25] Georgescu-Roegan (1971). See also a summary of his contributions in Beinhocker (2006).
[26] Beinhocker (2006) gives a synopsis of Georgescu-Roegen's ideas.
[27] There are many texts in ecology. For greater detail see *Fundamentals of Ecology* (5th edition; E. Odum and Barrett, 2005) and *The Systems View of Life* (Capra and Luisi, 2014) which give a much more complete treatments of the subject.

It is fairly easy to show that pollution in the environment and entropy are linked. Food is a source of energy, but uneaten it becomes garbage and begins to decompose. Like salt dissolving in water, smoke from a chimney disperses into the atmosphere. Georgescu-Roegen's ideas are thus applauded by most environmentalists and ecologists. His reception amongst his economic peers has been more uneven. Most of the economic arguments made against Georgescu-Roegen's approach are based in the neoclassical world-view that, as we've noted, views the economy as an equilibrium system rather than as a steady-state system.

Measuring the economy

Whatever the outlook, we need ways to measure the economy. The usual bulk measure is its Gross Domestic Product (GDP), for which a succinct working definition is provided by the government agency that measures it for the USA. According to the BEA[28], the GDP is "the output of goods and services produced by labor and property located in the United States"[29]. There are a number of problems with this definition. For example, should we include the labor involved in services such as child care or care for elderly parents as opposed to only counting labor when we pay for such services. Another problematic value, large in the case of the USA, is the "imputed rent" that the owner of a home doesn't have to pay in cash in order to live in a home that he or she owns[30] Note that both armament manufacture and health care for wounded soldiers are positive additions to GDP, despite a nagging suspicion that they should somehow have opposite signs; the same problem exists for the costs of environmental clean-ups and the industrial activity that resulted in the environmental problem in the first place.

The fact that the cost of an environmental clean-up and the activity which caused the need for the clean-up both contribute to GDP is because both use energy. In both cases, the use of energy results in an entropy increase. This example simply confirms that the economy can be viewed as a flow of energy.

[28] Bureau of Economic Analysis of the US Department of Commerce.
[29] This definition is as given in the BEA news release for the 2014 2nd quarter GDP figure at http://bea.gov/newsreleases/national/GDP/GDPnewsrelease.htm (accessed 2014-09-10).
[30] In the USA imputed rent is included in the GDP calculation.

Combining GDP from different countries leads to questions about how to include trade and what exchange rates to use (*e.g.*, nominal, purchasing power parity), particularly in countries which have fixed exchange rates. Finally, comparisons of GDP from year to year raise yet additional questions of how the underlying money may have changed from year to year. Adjusting the values by some inflation index is what is usually done, but such indexes and adjustments are just as problematic as is the single GDP calculation. Furthermore, any problem with an inflation index tends to compound, similar to compound interest. So the GDP numbers that are widely published in the financial news give a sense of what is happening, but they are not precise measurements and should be taken as but a rough indication of economic activity, especially when viewed over a length of time. Still, for all its faults, GDP is the best number available, so it is what gets used.

Energy and the economy

We're now in a position to examine more readily the relationship between energy use and GDP. As we do this, we need to keep in mind that many economic principles will only indicate the direction in which changes will occur, given that an equilibrium state will not be reached.

The first relationship between energy and GDP is that they are correlated; higher global energy production is associated with higher global GDP. This is to be expected, given that the economy (GDP) is a steady state at any given time. A small economy at a small steady state will use less energy than a large economy at a large steady state, all other things being equal. So as the economy grows from one steady state to the next, so too will the amount of energy used grow. This relationship is shown in figure 4-9.

Where the lines are not exactly parallel it means that the energy is being used more or less efficiently in the maintenance of the steady state. So Figure 6-8 shows that since 2000 there has been some improvement in overall energy efficiency, *i.e.* more GDP per unit of energy. The ratio of energy to GDP is more properly referred to as the "energy intensity".

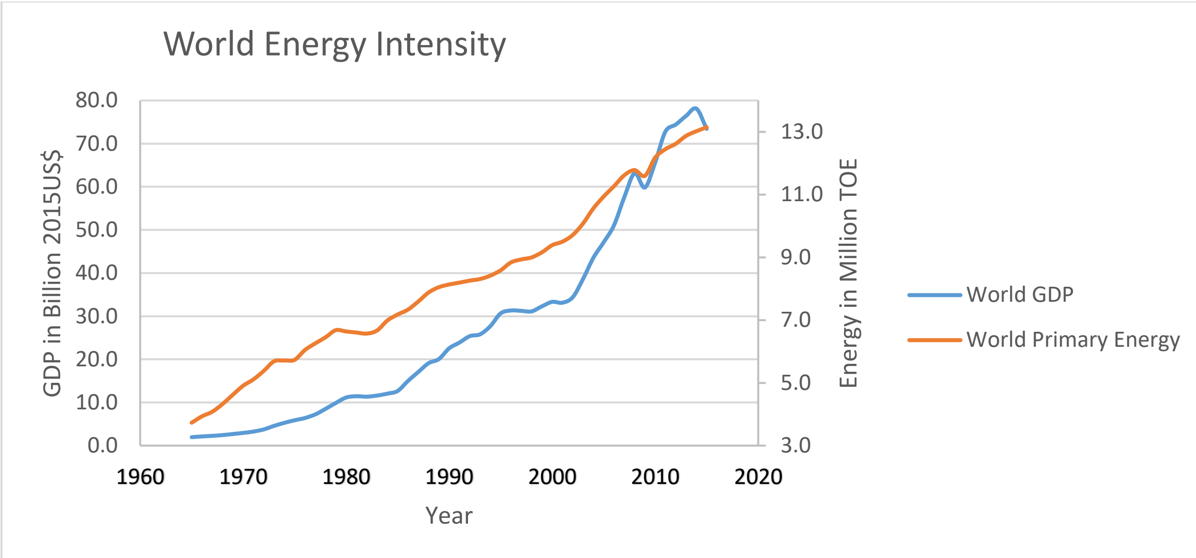


Figure 4-9 -- World energy intensity (data sources: World Bank, 2016, and BP Statistics, 2016)

Figure 4-10 shows these same relationships separately for OECD and non-OECD countries. Here we see that the intensity gain has been entirely in the OECD (*i.e.*, developed) economies (solid lines). In the developed economies the GDP has continued to increase since 2000 whereas Primary Energy in these economies has been almost flat over this period. But this improved Energy Intensity in the OECD countries is offset by a worsening trend in the non-OECD countries (dashed lines) where the Primary Energy use is increasing at least as fast as the GDP.

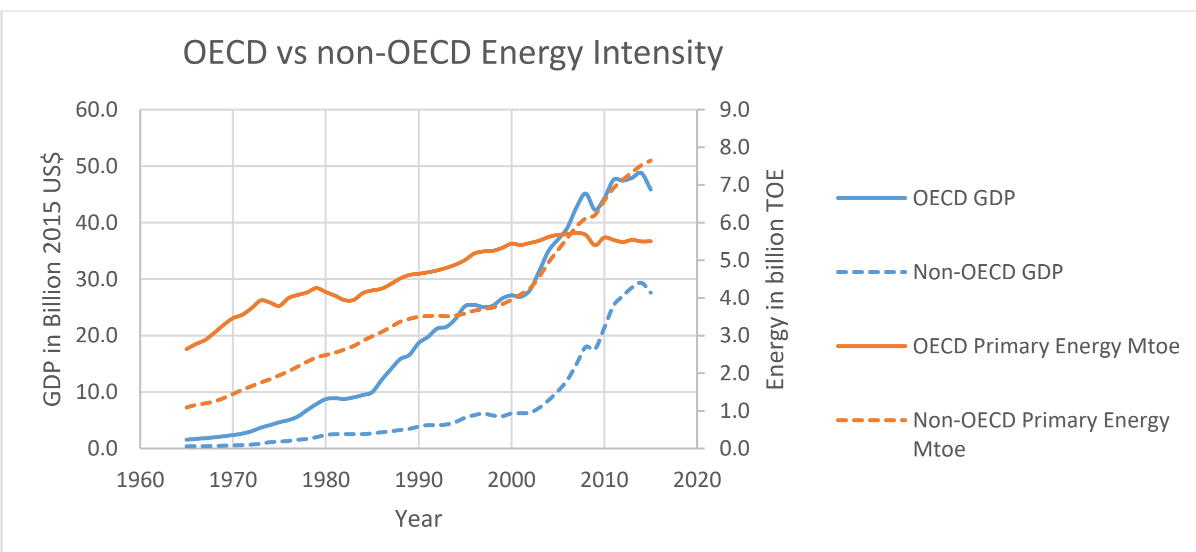


Figure 4-10 -- Energy intensity of OECD countries (solid lines) and non-OECD countries (dashed lines) (data sources: World Bank, 2016, and BP Statistics, 2016)

While the OECD countries are prone to boast about their recent increased energy intensities, the above trends can also be used to indicate that at least some of the OECD improvement has been due to selective transfer of energy intensive activities to non-OECD countries.

Globalization, which is a combination of trade rules, good communications and improved transportation, defines an open state system. This requires that measures of energy intensity be viewed from a global perspective; hence pollution and other entropy increases must also be viewed from a global perspective.

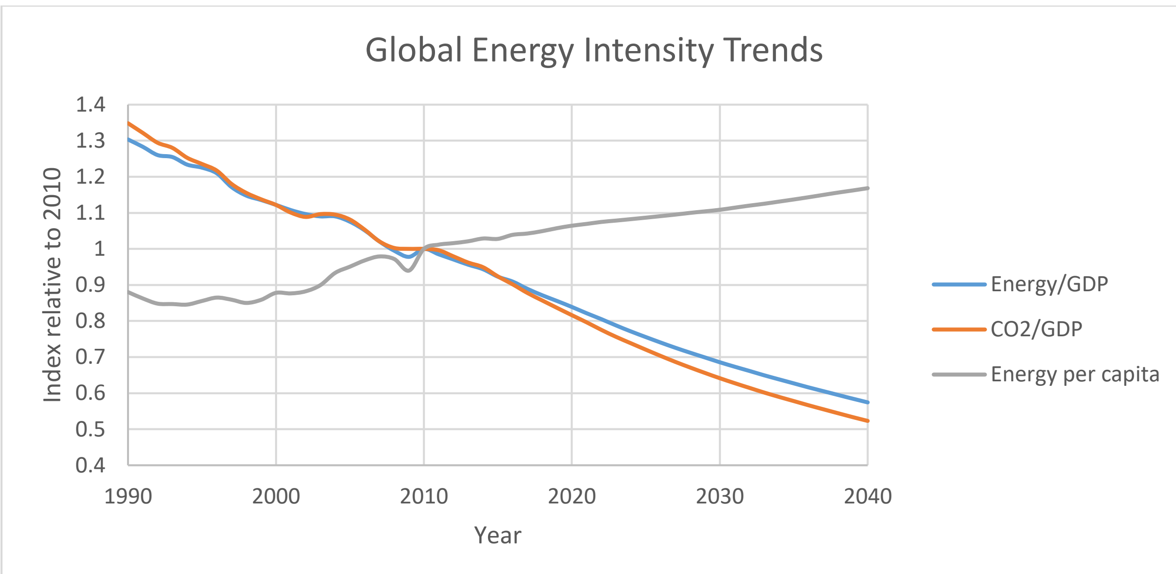


Figure 4-11 -- Global energy intensity trends (data sources EIA, 2023d; United Nations, 2015)

Figure 4-11 shows three different calculations of energy intensity for the world: the energy used per unit of GDP; the CO_2 emitted per unit of GDP; and the energy used per capita. Because most energy in the economy is obtained by burning fossil fuels, comparing the energy and CO_2 with respect to GDP are very similar. The increase in energy per capita reflects improved living standards. But ratios hide absolute values. Decreasing energy or CO_2 intensity can be due to increasing GDP rather than decreasing energy use or emissions. Hence figure 4-11 is not saying that the absolute amounts of energy used and CO_2 emissions in 2040 will be less than at present.

Another relationship between energy and GDP can be seen in the relationship between the energy price and the GDP. From the classical economic supply and demand model, one expects that when the price goes up the demand will go down and the supply will go up until a new equilibrium is reached. But economic models show that there is likely to be a significant time delay until the new supplies become available. The immediate effect will be that there will be less energy sold at the higher price. And because energy and GDP are correlated, the price increase will result in a lower GDP – a recession.

The International Monetary Fund (IMF) has plotted the oil price and economic recessions, which shows that recessions are frequently associated with high oil prices either just before or at the start of a recession. In particular the price increases associated with the fall of the Shah of Iran (1979) and the Gulf War (1990-1991) can be seen in figure 6-12, which plots data from 1974 to 2012.

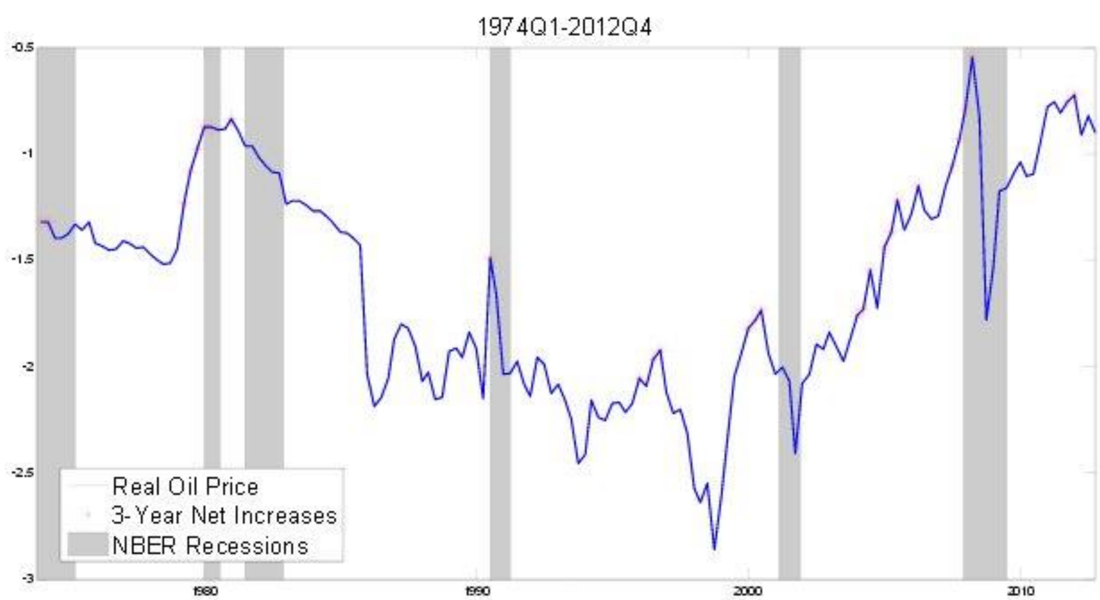


Figure 4-12 -- Oil price increases and recessions (Kilian and Vigfusson, 2014)

From 1971 to 1980 oil prices rose from $3.60 to $37.40, an increase of over 10 times. The economy did adjust to this increase, but only slowly. Cause and effect can be difficult to sort out; monetary and credit policy (Kilian and Vigfusson, 2014) also are important. Whatever the cause(s) of a recession, there are additional complications with respect to the oil markets. For example, the surge in exploration that resulted from high prices during the 1970s led to a glut of production in the 1980s. The high oil prices of the 1970s also appears to have permanently changed the trajectory of peak oil, as shown in figure 4-13

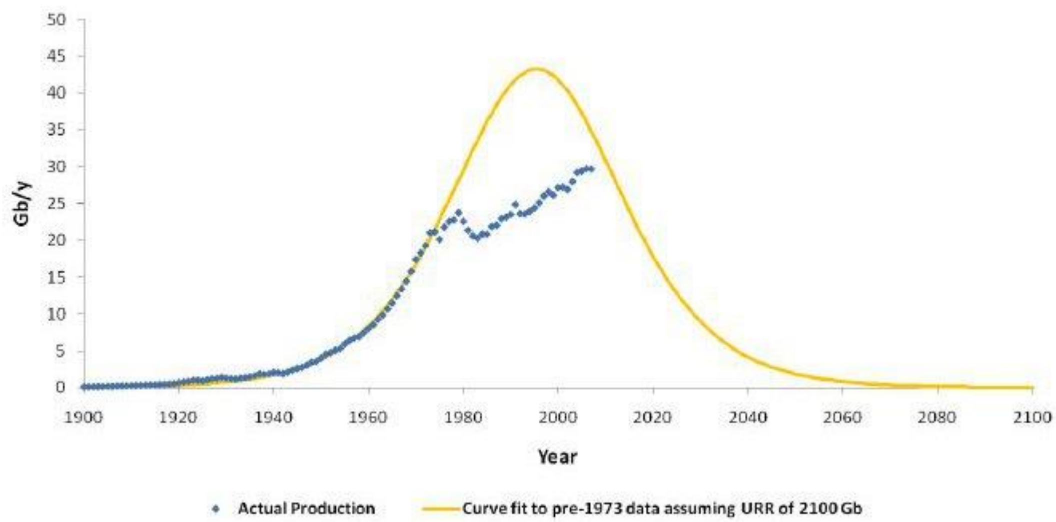


Figure 4-13 -- Oil production curve (Bentley, 2009)

The problem for economic planners, and therefore for politicians, is two-fold: first is the fact that as the finite resource of oil gets consumed, the marginal cost of new supplies goes up, and second is the fact that the project time-frames for energy projects makes any rapid adjustment to a new situation difficult at best.

Net Energy and EROI

Hubbert, of the peak oil theory, pointed out that no company will produce a barrel of oil if more than a barrel is consumed to produce it (Hubbert, 1982). This is, in essence, the definition of "net energy" (Peet and Baines, 1986)

Net Energy = Energy Produced - Energy cost

To make net energy numbers comparable, the cost portion needs to include three components: the energy used in developing the energy source, the energy used in ongoing operations, and the energy needed for eventual decommissioning. The calculation is done in energy units, for oil generally in barrels. But net energy is not much used because there are many other measurements available. For example, rather than considering the net energy of oil exploration, it is far easier to use figures such as reserves discovered or average size of new discoveries.

But a ratio using the same data as is required for net energy allows comparisons that are not available by other means. The most common is the Energy Return on Investment (EROI)[31], developed by Charles Hall from the 1970s on. The original concept was developed in ecological studies which describe the efficiency of trout in finding food to eat and being able to spawn the next generation.

The definition of EROI, analogous to the financial ROI, is:

EROI = (Energy Produced -- Energy costs) / Energy costs

which is to say

EROI = Net Energy / Energy costs

with energy costs comprising capital investment, operating costs and decommissioning costs, all in energy terms[32]. Using EROI we can compare projects across many different types of energy systems. Furthermore, because the EROI calculation is independent of time, calculation of EROIs for projects completed at different times can be compared directly without having to adjust for economic changes.

[31] Sometimes also termed EROEI (Energy return on energy invested) or EROIE (Energy return on invested energy).

[32] Somewhat similar to EROI is the Energy Return Ratio (ERR). Defined as simply ERR = Energy produced / Energy costs, the relationship between EROI and ERR is EROI = ERR – 1.

What matters is the Net Energy, that is to say the energy available to the overall economy. A comparison showing the percentage of Net Energy in relationship to the EROI is shown in

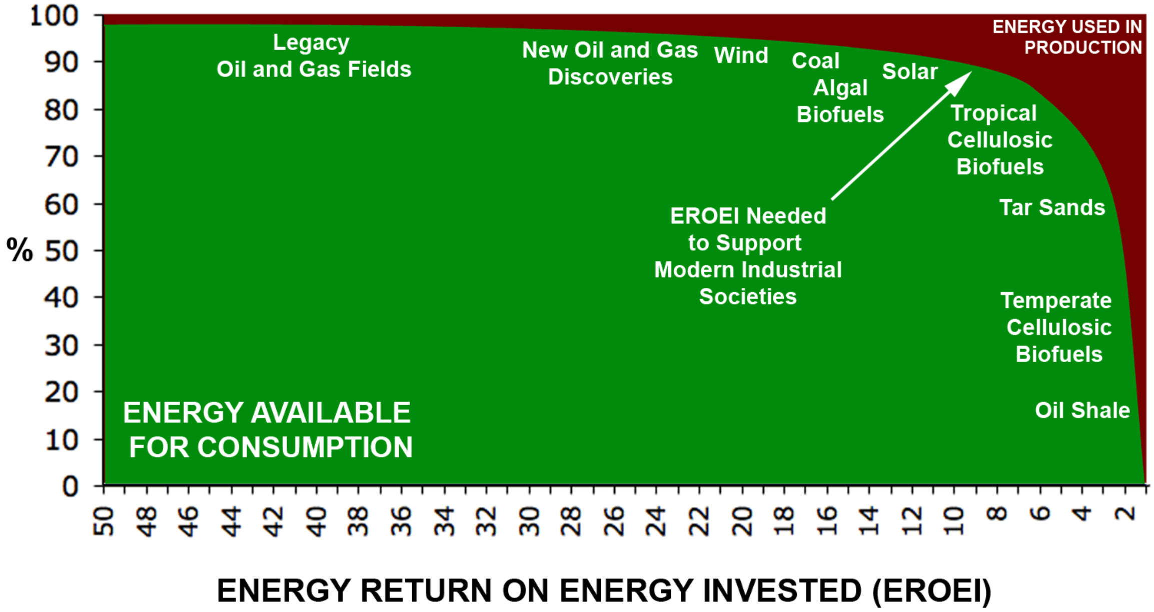


Figure 4-14 -- The Net Energy "cliff" (after Mearns, 2006, Murphy, 2011, and Mearns, 2016)

As the graph shows, the difference in Net Energy between an EROI of 50 and an EROI of 20 is not huge. A project with an EROI of 50 means that of 100 energy units produced, almost 2 will be used in the production of the energy, leaving 98 for the wider economy. A project with an EROI of 20 means that the project will provide a net contribution of only about 95. An EROI of 10 indicates the project will contribute only about 90 units. Lower than 10, the drop-off in Net Energy becomes very rapid, hence this graph is frequently called the “energy cliff” by analysts; a project with an EROI of only 1 will be consuming as much energy as it produces, and hence will not be contributing any energy to the wider economy. But note that the financial investments in an energy project with an EROI of 1 would still be counted as part of that country’s GDP, which thus might be considered the “event horizon” of energy economics by analogy to the event horizon around black holes found in astronomy (see Blundell, 2015).

The EROI, ERR and Net Energy numbers are always in energy units; the calculation is never done in monetary units. This means that financial ROIs and EROIs of a group of projects may rank in different orders. If an inexpensive, presumably historic, source of energy is used for the energy inputs the financial ROI may be significantly higher than the EROI. Some analysts argue that this is the current situation with respect to most of the "tight" oil and gas projects being undertaken today (*e.g.*, Smith, 2012). There is considerable discussion between economic analysts and energy analysts as to whether such differences between ROI and EROI can long be supported within an economy (*e.g.*, Nelder, 2012; King and Hall, 2011).

Economics of future energy

Earlier we discussed how any natural resource declines in quality the more that it is used. This is another way in which oil and natural gas are different from, for example, copper. One might construct a CuROI (Cu being the symbol for copper), that is the amount of copper needed to produced new copper. Or an AuROI, the amount of gold required in the production of gold. Just as for energy, these figures will become lower over time. But because of recycling, they do so relatively slowly (Bardi, 2014). Because of the Second Law, we can't recycle energy, and its EROI decreases faster. Over the course of the 20th century it is estimated that the overall EROI of oil fell from over 100:1 to somewhere around 20:1. The global economy is growing for three reasons: population growth, economic development in less-developed economies, and growth within most economies; growth in energy supplies is needed to support each of these. How the needed energy will continue to be supplied is one of the critical issues of the 21st century, more specifically the problems is how to continue to provide energy for the economy with a decreasing EROI that already seems to be dangerously close the "energy cliff". Remembering the Red Queen in Lewis Carroll's *Through The Looking Glass*, this problem is often referred to as the "Red Queen" effect – one must run faster and faster just to stay in the same place. As Garcia (2009) shows, it is possible to change the details of such projections in ways that appear to solve the problem, but the problem then simply reappears differently.

Projections[33] of energy supply and demand almost always examine the three issues mentioned: population growth, per capita energy usage growth and societal energy growth. The resulting GDP projection is correlated with energy consumption to give the total forecast of energy

[33] At least every projection of which I am aware that looks at total, global energy supply and demand. See IEA (2013, 2014a, 2014b), the Russian Academy of Sciences (Mitrova, 2013), ExxonMobile (2012), Royal Dutch Shell (2009).

demand. Some studies create several projections according to different scenarios. For example the IEA's 2013 *World Outlook* looks at three scenarios: a 'current policy' scenario, sometimes also called 'business as usual', which makes projections based on legislation, practices and policy currently in effect; a 'new policies' scenario which make projections based on legislation, practices and policy that have been announced by governments but are not yet implemented; and finally a '450 scenario' which presumes that governments will implement policies which will restrict atmospheric CO_2 to 450 ppm..

All of the various projections point to global GDP growth of between 3% and 4% over the coming decades. Oil is the critical component of the energy mix due to its role in transportation. As of today there are no major alternative energy sources available for large-scale transportation. This poses three quite different problems: the first is that it isn't clear that such growth will be able to be maintained given the decreasing EROI values for oil; the second is that if the declining EROI values don't result in energy shortages it means that there will be far too much CO_2 released into the atmosphere to allow meeting the 450 ppm CO_2 limit that is the maximum that can be tolerated without run-away global warming, and finally given the long capital investment lead times for energy projects there are concerns that there simply isn't sufficient time to make changes. Table 6-2 shows recent (2013) distribution of energy sources.

Table 4-2 -- World sources of energy 2023 (sources: Energy institute (2024) and BP statistics (2018)

Energy Source	Exajoules[34]	Percent of total	Average percentage growth last 6 years
Oil	190.7	31.6%	-1.1%
Natural Gas	141.9	23.5%	7.7%
Coal	161.5	26.7%	3.7%
Total Fossil Fuels	494.0	81.8%	2.9%
Nuclear	24.1	4.0%	-3.5%
Hydropower	40.7	6.7%	5.6%
Total renewables	45.2	7.5%	120.2%
Grand total	13,1058.1	100.0%	2.4%

If the GDP growth of between 3% and 4% is to be achieved, and the 450 ppm CO_2 limit also honored, then the non-fossil fuel components of total energy will need to go from being less than 20% of total energy at present to virtually all of it within two decades. The nuclear contribution will be limited in OECD countries due to political constraints, and sites for major new hydroelectric projects are rapidly declining. Which leaves major contributions from other renewables as the way forward. While some of these have grown rapidly over the past 5 years, there is some concern as to whether these growth rates can be sustained. For comparison, mobile phone accounts, which over the past 2 decades have virtually exploded, have been growing at a rate of about 10% per year (Kearney, 2013).

[34] Converting everything to exajoules (10^{18} joules) allows analysis, but has many methodological problems. For oil, average values of weight per barrel and energy per barrel are generally used as a starting point, but different sources use different average numbers. Similar to oil, average values are used to convert natural gas and coal to their energy. It gets more complicated when there is no fuel being burned. The heat generated by a nuclear reactor is generally known; because this heat is used to make electricity in the same way as is heat from burning coal, the calculation of toe from heat value is still relatively straightforward. Renewables, including hydropower, where the applications and technologies are different pose additional problems. Typical thermal electricity generation has an efficiency of about 33%, so often the electricity output from such sources is divided by a figure of between 2.5 and 3.5 to arrive at a comparison figure. But this presumption and division is only sometimes done, making comparisons tricky. See American Physical Society (2014) and Marinot et al (2007) for a more complete discussion.

To sum up, unlike other resources that society uses, energy generally cannot be recycled. Furthermore, as with all resources, the energy sources that provide the best return are the ones that get used first. Population growth coupled with a rising standard of living point to global GDP growth over coming decades. The growing GDP requires more energy, while at the same time declining EROIs mean that the need for energy grows even faster than the GDP growth.

Chapter 5 -- Environmental issues with Fracking

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Hydraulic fracturing or "fracking" overlays a major industrial operation on the land in areas where shale and tight hydrocarbon resources can be exploited. Every aspect of the fracking operation can cause environmental damage, although the damage from any individual well is both unlikely and usually fairly limited. Such damage has been extensively documented, giving the impression that fracking activity is bad for the environment. There is no yes or no answer to the question "Is fracking harmful to the environment"; rather, it is an issue that must be resolved politically for the area involved rather than scientifically.

Introduction

"Fracking", or as the oil and gas industry prefers, hydraulic fracturing, is the result of combining two petroleum exploitation technologies, both of which have been used and developed for decades. The first of these is horizontal drilling, which began as directional drilling to allow multiple wells from a single offshore platform to reach their completion depths with precise separations in the hydrocarbon-rich zones. This has progressed to drilling horizontally at depth, where the well bore follows the productive interval for several kilometers. The second is hydraulic fracturing[35] using "slick water" to increase the permeability of rocks previously considered too impermeable to economically produce hydrocarbons.

The use of the combined technologies was rapidly developed in the first decade of this century, with Mitchell Energy Corp.[36] developing the technologies in the Barnett Formation (a gas play) of northeast Texas (Gold, 2014, p. 120-122). This was followed in the Marcellus Formation (a gas play extending from Kentucky to New York, but developed primarily in Pennsylvania, Ohio, and West Virginia), the Bakken Formation (primarily light oil in North Dakota, extending into Montana and Saskatchewan), the Eagle Ford Formation (both oil and gas in Texas, extending into Mexico), and the Permian Basin (oil with associated gas in Texas and adjacent New

[35] Hydraulic in its meaning of any fluid; for example, as in hydraulic press.
[36] Since acquired by Devon Energy.

Mexico). Many other plays have been exploited to a greater or lesser extent in the USA, and to some extent in Canada, Argentina, and China with prospects in many additional countries. Each formation has posed its own operational problems, and industry has quickly developed effective technologies which it continues to improve upon.

The technologic challenge is to extract the fluid hydrocarbons, either oil or natural gas, from shales and tight siltstones, rocks of very low permeability. Many of these shales have been geologically known as containing hydrocarbons for decades, frequently because they are the source rocks for conventional oil or gas fields. But their very low permeability had made them uneconomic for traditional hydrocarbon exploitation. The combination of horizontal wells and hydraulic fracturing has made these economic for exploitation; the resulting production is shale oil[37] or shale gas[38].

There has been a significant backlash to the widespread use of these new technologies on environmental grounds. In the past 20 years there have been many thousands[39] of peer-reviewed scientific papers presenting data related to fracking operations, plus numerous government reports, professional technical presentations, and other investigations. To this should be added a very large number of blog posts of varying quality. The debates about fracking are not entirely a scientific question; questions of social and economic impacts are part of the discussion.

[37] Shale oil should not be confused with oil shale, which is very different. Oil shale is shale rock that contains solid hydrocarbons not yet transformed into liquids by geologic heat and time; to obtain oil from an oil shale the rock must be heated; the technical challenges have not yet been solved to allow economic extraction from oil shales. In contrast, shale oil is liquid oil produced directly from a rock that is shale; the technical challenges of extraction from this very impermeable rock have been met by fracturing.

[38] Also sometimes "tight oil" or "tight gas" when the rock is not strictly a shale.

[39] See, for example, PSE (2020) The ROGER Citation Database, https://www.zotero.org/groups/248773/repository_for_oil_and_gas_energy_research_roger_-_pse_healthy_energy_collections/RWRMA2FU/items/9EMGA46W/collection (accessed May 14, 2020) or Concerned Health Professionals of NY and Physicians for Social Responsibility (2019) Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking (Unconventional Gas and Oil Extraction), 6th edition http://concernedhealthny.org/wp-content/uploads/2019/06/Fracking-Science-Compendium_6.pdf (accessed July 24, 2019) or G.E.King (2012) Hydraulic Fracturing 101, Conference presentation at SPE Hydraulic Fracturing Technology Conference, https://www.onepetro.org/conference-paper/SPE-152596-MS (accessed 25 Feb. 2020), doi:10.2118/152596-MS.

We attempt in this paper to use “fracking” to describe the entire suite of activities involved in the exploitation of tight or impermeable hydrocarbons, and “fracturing” to refer to the

Table 5-1 -- Technical terms used in connection with fracking

Completion	The actions taken once a well has been drilled that will allow it to produce hydrocarbons
Connate water	Water, usually a brine, found to some extent in all rocks at depth
Continuous deposits	Hydrocarbon source rocks that only can be exploited by fracturing in contrast to conventional deposits (meaning 1)
Conventional	Two meanings: 1) situations where hydrocarbons have been concentrated over geologic time into relatively permeable strata, and 2) wells that are primarily vertical rather than having horizontal sections. Note that definition 2 oil and gas wells are frequently fractured in their pay zones
Cuttings	Bits of rock brought to the surface during drilling of the well
Flow back	Fluid used for fracturing that returns to the surface when the fracturing pressure is released
Fracking	All hydrocarbon extraction activities requiring the use of fracturing to increase permeability and thus make the exploitation economic
Fracturing	Using hydraulic pressure to break rocks at depth, thereby increasing their permeability
Horizontal well	The portion of a well which follows a specific geologic stratum or horizon
Hydraulic fracturing	(see fracturing)
Hydrocarbon	Oil or natural gas; chemically any chemical composed of hydrogen and oxygen
Lateral	(see horizontal well)
Operator	An oil or gas company that produces hydrocarbons for economic benefit
Pad	An area, generally about 1 to 3 hectares (2.5 to 7.5 acres) from which multiple wells are drilled and operated
Pay zone	The geologic strata that contain the hydrocarbons being exploited
Permeability	A measure of the ease with which fluids can flow through a solid. See also porosity.
Play	A geological formation coupled with a set of ideas that support hydrocarbon production
Porosity	The space between constituents of a solid which may contain something else, usually a liquid or a gas. See also permeability.
Produced water	Water produced along with exploited hydrocarbons
Production	The economic hydrocarbons coming from a well; depending on context production may or may not include associated water
Shale	Fine-grained sedimentary rock, almost always impermeable. Shales are the sedimentary source deposits for hydrocarbons
Vertical well	A well drilled vertically down from the surface; this may be completed as an oil or gas well, or may then be ‘turned’ to become a horizontal well at depth
Well head	The surface location of the well

specific breaking of the rock using fluid pressure. Table 5-1 is a brief glossary of technical terms used; figure 5-1 illustrates the concept and context of fracking, and figure 5-2 shows a well pad. Note that figure 5-1 is not to scale; in particular, in most plays the distance from the water table to the stratum being fractured is many times the thickness shown, fissures preferentially form horizontally rather than vertically. In figure 5-2 note the significant excavation at the far side of the pad and fill at the near side to create a level work area.

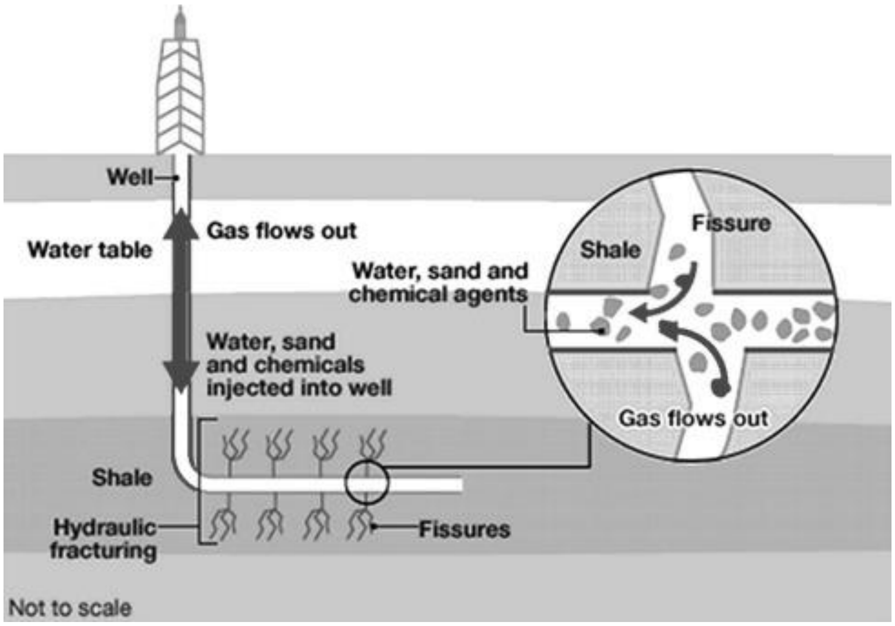


Figure 5-1 -- Schematic diagram of fracking (after Hammond and O'Grady, 2017)

Figure 5-2 - Aerial photo of a pad (after Butler, 2018)

Life cycle of a fracked well

The environmental issues that surround fracking change over the life cycle of a well. The basic stages are site selection and preparation, drilling the well, completing the well (which includes the fracturing operation itself), producing the well, and eventual abandonment and site restoration.

Site selection and preparation

Even with hydraulic fracturing technology, the very low permeability of the target strata requires that wells be located close together. This is most economically done by concentrating the surface installations for multiple wells in a single location – the well pad. This can be thought of as an on-shore platform. The number of wells that the pad can support will vary, but pad design generally supports a minimum of 4 wells, and usually will support more. A total of 8, 12 or 16 wells is common, depending on the specifics of the target formation. As with an offshore platform, pads are constructed after the production potential of the play has been established.

Site selection for the pad starts with assessment of mineral rights ownership and seismic information. The specific site must provide a secure base for all of the equipment that will be involved; construction of a well pad thus requires civil engineering expertise to create a strong, level, and well-drained foundation for a 1 to 3 hectare (2.5 to 7.5 acre) work area. Construction of the well pad itself must consider preserving natural drainage, creating barriers to contain any accidental spills, and generally minimizing damage to existing ecosystems. Environmental considerations during pad construction will be similar to those for other civil engineering projects, with the addition of placing impermeable barriers and constructing drainage to ensure that spills and runoff do not contaminate surface or ground water. Erosion control due to disrupted land cover, modifications to drainage, and the noise of heavy construction equipment will all be factors in pad design. Because the presumption is that a well pad is a temporary rather than permanent feature, although it may be in use for several decades, site construction normally includes provisions for restoration of the land surface and drainage to its original state, and will provide for preservation or replacement of topsoil and replanting. We again emphasize that the specific requirements at a site will vary somewhat with the specific jurisdictions; the permits needed in Pennsylvania are shown in table 5-2.

Table 5-2 -- Permits, regulations and other requirements for oil and gas operations in Pennsylvania. The table is indicative, not definitive. Modified from https://pioga.org/education/oil-and-gas-regulations/ (accessed 2020-05-07)

Description	Regulation or Permit	Government level
Well drilling permit: -- complete location, depth, casing cementing plans -- notification to all interested parties -- posting of bond -- approval of any waivers -- emergency response plans -- on-site sewage facilities	Permit	State, with local and/or federal requirements for some aspects
Waste handling: -- onsite waste management -- waste transfer facilities -- haulage requirements	Regulation	State, with local and/or federal approvals required
Road occupancy and use -- temporary access roads -- pipeline crossings	Permit	State, sometime local
Pits and impoundments -- water or mud pit berms may be considered as dams -- liners must meet standards	Permit and/or regulation	State, some federal and/or local requirements
Water use and discharge -- water management plan required	Permit and/or regulation	State, federal, and/or interstate compacts
Air emissions -- applies to both well sites and pipeline operations	Permit	State, embodying federal standards; exemption from state requirements does NOT exempt from federal rules
Wetlands protections -- required for modifications and/or crossings	Permit	State and federal
Erosion and sedimentation controls -- applies to both pads and pipelines	Permit	State
Miscellaneous -- endangered species protections -- cultural resource protections	Regulations	State and federal
Water use permit	Permit	Varies with specific site, multiple permits may be required[40]

Each of the issues in table 5-2 includes a long list of detailed subsidiary regulations which must be addressed in permit applications. Figure 5-3 illustrates the result in one case. The operator could not obtain a permit to have a temporary access road cross the wetlands, with the result

[40] E.g., the multi-state Susquehanna River Basin Commission in addition to local jurisdictions.

that a much longer access route, with a weight limit of 25 tons, was required; direct access would have required a route of ca. 0.7 km in contrast to the final route of 5.3 km.

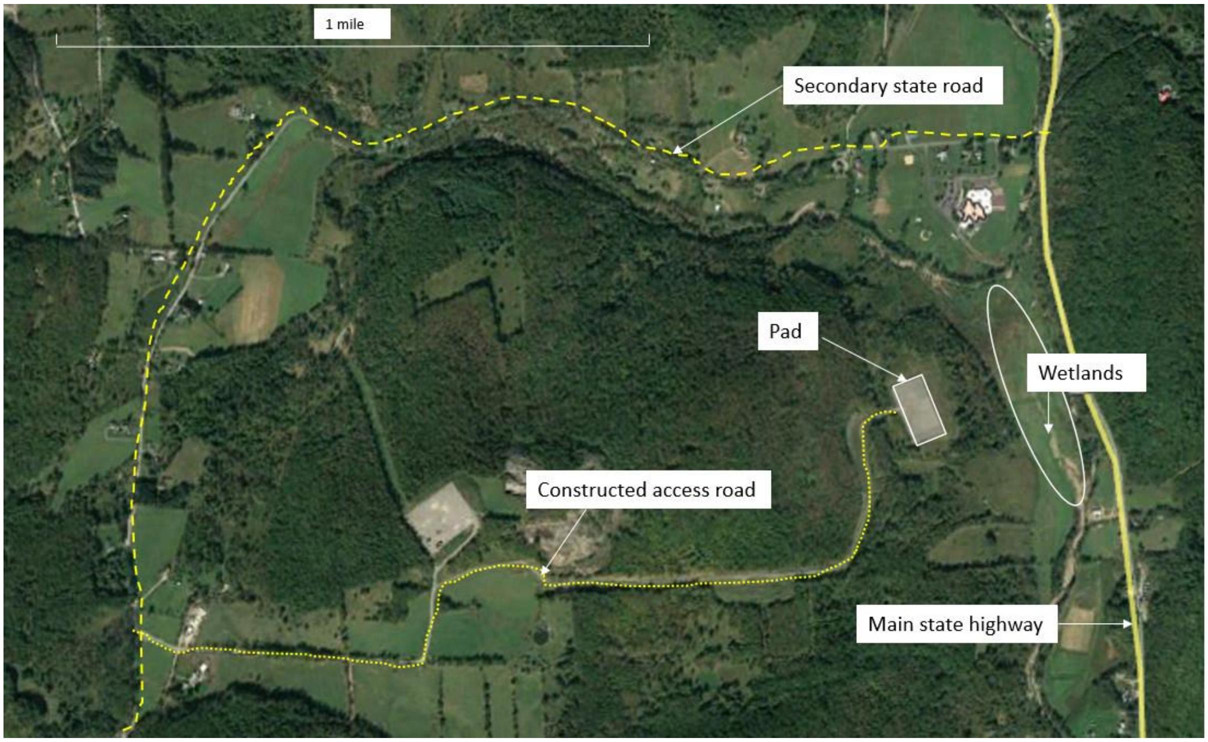


Figure 5-3 -- Environmental modifications required for a pad site. Source: Google Earth (2020) with annotations by the author (SWC) based on personal conversations with the landowners involved.

In other states there may be other agencies involved. For example, US Indian tribes and/or the US Bureau of Indian Affairs may be involved; different US agencies may be involved in the case of federal lands, depending on how the land is classified; the US Army Corps of Engineers may be involved when there are impacts to navigable watercourses; in some states local restrictions may be imposed in addition to state-level requirements. The operators complain about the overlay of these different levels of regulation. But oil and gas regulations exist almost everywhere (Rabia, 2019), many of which are either directly or indirectly designed to protect the environment. To date, fracking has not been economic in offshore environments, i.e., from offshore platforms[41]. Neither have continuous plays been developed outside the USA.[42]

Drilling the well

The actual drilling of wells uses techniques that have been deployed for decades. There are two major differences in fracking operations: first, that the well will be deviated, "turned", at depth so as to follow a specific geologic stratum for thousands of feet and second, a number of wells will be drilled from the same surface location. The drill pad is an active, heavy-industry operation during drilling and fracturing. It will operate around-the-clock, making issues of noise and traffic significant. The actual drilling will seldom take more than a month for an individual well; modern practice frequently is to use one rig to drill vertically down to the point where the well will be turned, which is often a matter of a few days, and then use a different drill rig to "turn" the well and drill the horizontal section. This division of the drilling into two separate operations is only possible after the geology of the strata are reasonably well-known.

During the actual drilling a mud slurry, "mud", is pumped down the center of the drilling pipe[43,44]; this both cools and lubricates the actual drill bit, and is sufficiently thick to carry the bits of drilled rock, "cuttings", back to the surface as it flows up around the outside of the drill stem. The mud flow may also be used to power the rotary bit itself. Periodically the drilling stops and casing is inserted into the drilled well. The annulus between the casing and the surrounding rock is filled with cement, and the drilling recommences at a smaller diameter. Figure 5-4 shows some idealized well constructions for vertical wells; horizontal wells follow the same principles. Important is that almost all jurisdictions require that surface casing extend to a depth below the deepest known aquifer (Rabia, 2019)[45]. At various levels casing is set, with

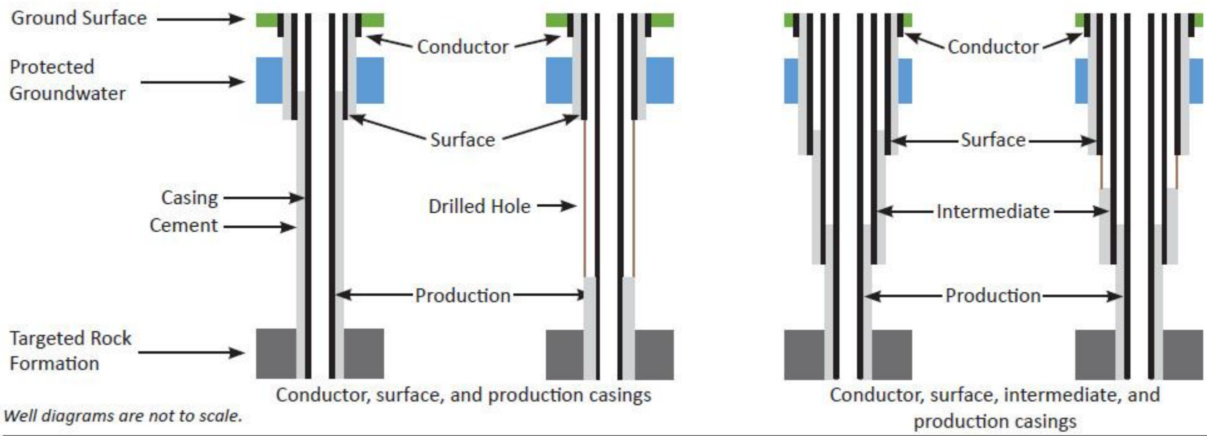
[41] Fracturing is routinely used offshore in conventional wells; it is the unconventional, continuous deposits which require long lateral well segments that have not yet been economically exploited offshore.
[42] There are exceptions, notably in Canada, Argentina, and China, but to date the extent of fracking activity in these plays has not been extensive.
[43] When the initial vertical well is drilled separately, compressed air sometimes is used instead of mud.
[44] Generally called the drill stem.
[45] This is not clear in the case of groundwater contamination above the Barnett Formation play in Texas which may have been due to failure to case wells through the aquifer being used for drinking water. In that area, the aquifer has two zones, and the protective casing may only have been set to below the upper zone. Gold (2014) 98.

cement used to seal the surrounding rock from the interior of the well. As shown in figure 5-4, this may be done repeatedly.

Obvious from the figure is that the integrity of the cement is critical in preventing contamination of groundwater aquifers; cement is also critical when high pressures are

Well Construction Characteristics

Wells are typically constructed using multiple layers of casing and cement. The subsurface environment, state and federal regulations, and industry experience and practices influence the number and placement of casing and cement.



Oil and Gas Production Well Dictionary

Casing	Steel pipe that extends from the ground surface to the bottom of the drilled hole
Cement	A slurry that hardens around the outside of the casing; cement fills the space between casings or between a casing and the drilled hole and provides support for the casing
Conductor casing	Casing that prevents the in-fill of dirt and rock in the uppermost few feet of drilled hole
Intermediate casing	Casing that seals off intermediate rock formations that may have different pressures than deeper or shallower rock formations
Production casing	Casing that transports fluids up and down the well
Surface casing	Casing that seals off groundwater resources that are identified as drinking water or useable
Targeted rock formation	The part of a rock formation that contains the oil and/or gas to be extracted

Figure 5-4 - Schematic drawing of well construction details (after US Environmental Protection Agency, 2016)

encountered during drilling. Both the Macondo blow-out in the Gulf of Mexico in 2010[46] and the contaminated aquifer issues in Dimock, PA, popularized in the film *Gasland*, have been traced back to cement problems.[47]

[46] US Chemical Safety and Hazard Investigation Board (2016) Report 2016-04-12 Executive Summary p. 6 "Earlier, a critical cement barrier intended to keep the hydrocarbons below the seafloor had not been effectively installed at the bottom of the well. ".

[47] Pa DEP Consent Order and Decree Nov. 4, 2009, available at https://s3.amazonaws.com/propublica/assets/natural_gas/final_cabot_co-a.pdf?_ga=2.157896178.998274142.1589362599-1169587268.1589362599 (accessed 2020-05-13). At p. 3 the decree has "... Department issued Cabot a Notice of Violation for failing to properly cement casing at certain of the Cabot Wells, and for failing to prevent gas from entering groundwater from the Cabot Well ...".

The mud slurry circulated during drilling is carefully engineered so that its properties will be a good match for the rocks through which the well is drilled. Different types of mud work best in different types of rock, and in addition to the basic constituents of water and dry clay powder, specific chemicals may be added to the mixture. The volume of mud needed to drill a well is significant, but seldom more than 2,000 m^3; by comparison an Olympic-sized swimming pool (50 x 2 x 25 meters) holds 2,500 m^3 of water. As the mud circulates, the cuttings are separated out. Historically, the mud was created by mixing dry clay with water in an open pit. While still called the 'mud pit', modern practice always requires that this be lined with very heavy-duty plastic to prevent any seepage down into aquifers; frequently today's mud pits are not open but are large, enclosed containers or tanks. While the circulating mud is contained within a closed system, leaks and spills can and do occur, creating possible contamination issues. Eventually, both the cuttings and the mud require correct disposal; re-use of the mud itself in adjacent wells is possible, which minimizes the disposal problem.

The volume of cuttings will vary depending on the depth of the vertical portion of the well and the length of the lateral portion. Amounts vary, but a typical Marcellus well is likely to produce between 350 and 400 metric tons of cuttings (Stuckman et al., 2019). Cuttings are generally dried and then used as landfill or for construction purposes, and are frequently exempt from US Environmental rules governing hazardous wastes (EPA, 2002). The organic-rich shales that are targets of fracking frequently contain toxic elements, notably arsenic, barium, and uranium; landfills sometimes reject loads of cuttings because radiation levels are too high (Phan et al., 2015). When dried cuttings eventually are exposed to weathering, for example when they are used as fill in construction projects, they may release these and other toxic elements – sometimes into runoff water and sometimes by seepage into aquifers used for drinking water (Concerned health professionals, 2016).

Completion activities

In conventional reservoirs, fracturing is simply an early step in the overall completion process; in wells that will be completed in shales, it is a major activity by itself. Prior to fracturing, the final design of the well will be completed; this may involve the final cementing job, installing the final set of casing, perforating the final casing where it is in contact with the hydrocarbon-rich strata, and installing at least sufficient surface equipment so that the well can be tested.

The fracturing operation

The basic technique of hydraulic fracturing is to pump fluid into a well until the pressure becomes sufficiently great that the rock breaks at the target level. A small amount of sand, frequently natural but sometimes a manufactured ceramic, is added so that when the pressure is removed the fractures remain open, hence the name “proppants”. Added to the water are small amounts of chemicals: to reduce internal friction; to prevent any algae and bacteria in the water from growing; to prevent the water from causing rust or other corrosion to the metal casings; and sometimes as a treatment for the specific rock formation being fractured (FracFocus, 2020).

One of the major technologic breakthroughs was the use of fresh water as the basic fracturing fluid, with an additive to reduce internal friction, hence “slick water”[48]. The amounts of water needed vary considerably, from ca. 2,000 m^3 to 100,000 m^3 (USGS, 2019; Petrol. Services Assn. Canada, 2019). While normally 1% or less of the total fracturing fluid (Zendehboudi and Bahadori, 2015), the additives used in the fracturing operation have been the subject of much controversy. Companies which conduct fracturing operations have exacerbated the controversy by responding to requests for information about the additives by refusing to identify the exact chemicals and proportions used on the grounds that these are competitive trade secrets (Maule et al., 2013). Indeed, some of the chemical additives are toxic (Stringfellow et al., 2017) and/or carcinogenic (Chen and Carter, 2017), in particular, biocides needed to control algal and bacterial growth in the well are designed to be toxic. To help alleviate public concerns, the industry in the USA has established a public database showing the details of additives for each well (FracFocus, 2020).

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[48] The effect had been used elsewhere, for example in firefighting. E.Blum (1969) Slippery Water: A Documented Advance in FireFighting Technology; Rand Corporation Report D-18684-NYC https://www.rand.org/content/dam/rand/pubs/documents/2008/D18684.pdf (accessed 2020-05-18).

During a fracturing operation the fluid pressure in the well is increased until the rock at depth physically breaks. One environmental concern is that these breaks will extend upwards into drinking water aquifers, or perhaps to the surface, thus providing a pathway for both the hydrocarbons and the fracking fluids to escape to shallow depths or even the surface. Whether this is likely to happen depends to a large extent on the vertical distance separating the bottom of the deepest aquifer and the top of the shallowest fractured stratum. As is expected, the greater this vertical separation, the less likely that such a break will extend across the entire vertical distance (Davies et al., 2012). The actual propagation distance will depend on the specifics of the rocks involved. Davies et al. suggest less than 1% of fractures will progress more than 300 m in the Marcellus formation; Flewelling et al. (2013) report that no seismic indications of fractures have been observed more than 600 m above the fractured formation, and Fisher et al. found more than 750 meters separation between the top of fractures and the deepest aquifers in four plays (Fisher and Warpinski, 2011). The horizontal extent of fractures is much greater than their vertical extent (Fisher and Warpinski, 2011), which is expected due to the horizontal fabric of sedimentary rocks. When natural vertical fractures exist in the rock there is a small chance that they extend into aquifers or to the surface, but most are found to be of approximately the same length as hydraulically induced fractures (Fisher and Warpinski, 2011).

Much more likely are problems created by the well itself or other nearby wells. When the hydraulic pressure is applied to fracture the hydrocarbon-bearing rock it can also break the materials of the well. Ruptures of materials of the well itself are collectively called ‘well integrity problems’. The most common is that the cement used to form a seal between each of the casing layers and the surrounding rock or next larger casing (see figure 5-4) has been improperly applied or has not properly set. An example from a Marcellus well in Pennsylvania (Moore et al., 2012) found that cement had failed to set properly along an intermediate portion of the well with the result that gas was escaping up through the cement to the surface. Concerned that such gas leaks might also contaminate the aquifer used for drinking water in the area, the Pennsylvania regulators would not allow fracturing to take place until the leak issues had been resolved. The typical solution to such defects is to perforate the casing and “squeeze” additional cement into the annulus. In this case this was not required because the operator was able to demonstrate that the leakage remained isolated from both the shallower aquifer and the targeted gas layer at depth (Moore et al., 2012). Cement takes time to set and form a barrier. Although not specifically a fracking issue, not taking the time to properly assess the quality of a cement job led to the Macondo blowout and criminal charges against the operator and some of the operator’s employees (Gold, 2014, p.275). King and Valencia (2014) point out that despite the fact that no cement job is likely to be perfect, the multiple layers of cement in typical well construction mean that well integrity is almost always sufficient.

While poor cement in the well itself can cause problems, another route to the surface that the fracturing operation may create is to other wells, both presently operating wells and abandoned wells. When the fractures created by the fracturing operation intersect the fractures created in a neighboring well the result is a “frac hit”. When a play is developed by fracturing, the lateral portions of adjacent wells may be less than 300 m (1000 ft) apart (see figure 5-5). This has been known to cause “blowouts” in another well, which may have a surface location several miles away from the surface location of the well being fractured (Jacobs, 2017). Once wells have been put on production, some of the safety equipment available to contain high pressures frequently has been removed; several states now require an operator to notify all nearby well operators of fracturing operations.[49] But even without a blowout, both nearby wells and the new well being fractured may be damaged by the loss of pressure from a frac hit, thus diminishing the economic value of both wells (Jacobs, 2017).

[49] Distance requirements vary by state.

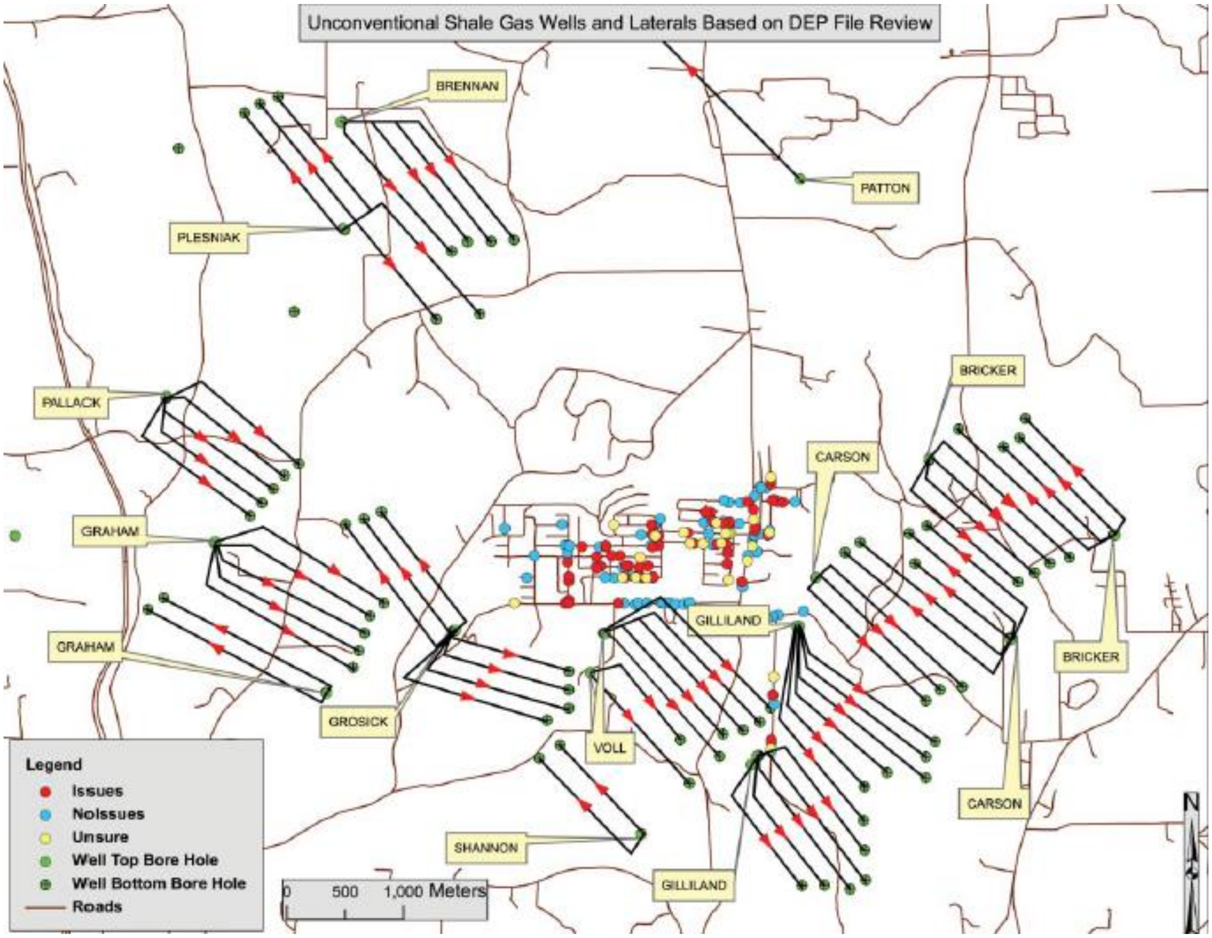

Figure 5-5 -- Pads and traces of horizontal wells in a portion of Lancaster and Connoquenessing townships, Butler County, Pennsylvania as of 2012 (after Alawattegama et al, 2015)

Figure 5-5 illustrates how close the lateral portions of wells can be. See also G. Aisch (2014) *What North Dakota would look like if all its oil drilling lines were aboveground* https://www.nytimes.com/interactive/2014/11/24/upshot/nd-oil-well-illustration.html (accessed 2020-05-20) which provides an interesting visual perspective of the closely spaced lateral wells in an area of the Bakken play.

Similar to frac hits is the problem of having fractures created in the fracturing operation extend into abandoned wells, which then provide an easy path to the surface. King notes that well engineering practices, including abandonment practices, have changed over the years (King, 2015). Particularly in the Pennsylvania and Ohio areas of the present Marcellus and Utica plays the industry has been drilling oil and gas wells for more than 150 years; some locations of old wells, along with pollution problems they may be causing, may be unknown (King and Valencia, 2014).

At the end of the fracturing operation, when the pressure is released, some of the fluid pumped into the well to cause the fracturing will return to the surface. Not only will this fluid contain the additives mentioned above, but it will be mixed to a greater or lesser extent with fluid which has been in the rocks at depth. Because of the mixture with formation waters, this water is generally a brine with components that require that it be processed before it can be discharged to the environment (Lester, 2015; Abualfaraj, 2014).

Other completion steps

Once the fracturing is completed, the well must be tested, in part to see how successful the fracturing operation has been. The testing will determine the flow rates the well can sustain. Then pipeline connections, storage tanks, separators, compressors and other equipment must be installed. The major environmental issues that arise during this phase are proper disposal of whatever comes up the well. This may include flowback of some of the fracturing fluid and initial amounts of hydrocarbons mixed with water present in the subsurface strata being exploited.

One of the early and important tasks during completion is to test the well to see what volumes it can produce on a sustained basis. Because the well is not entirely ready for production, gas typically is flared and fluids put in temporary storage tanks. The tests may last for several days. Flaring is environmentally problematic, particularly in more densely populated areas, with particulate soot, light and noise pollution (Fawole et al., 2016; Troutman and Pribanic, 2011) which are known to cause health risks (Babisch et al., 2005).

Producing the well

Once the testing of the well has been completed, the well will be shut until all of the production equipment is installed, perhaps waiting to include equipment for wells still being drilled on the same pad. If final production plans require the hydrocarbons to be delivered by pipeline, the pipeline will need to be constructed, otherwise necessary storage tanks will be constructed.

When all the pieces are in place, the well will be put into production. The major environmental concerns during production are leaks, the most important of which is escaping methane because of its large greenhouse gas contribution. Another environmental concern during production is noise associated with gas, either from flaring associated gas or for compressors when the gas is being sold.

Fracked wells are notorious for their rapid decline rates. Nevertheless, any specific well can be expected to produce for at least a decade, and probably several, although at very low rates going into the future. Provided there is good maintenance, these decades of production are the least environmentally problematic in the life cycle of the well. But there will come a time when the revenue being generated is insufficient to continue production, and the well will be shut in awaiting price recovery, or abandoned.

Abandonment and site restoration

There are well-established procedures for well abandonment with regulations governing the process, again mostly at the state level in the USA. But there is a problem. At this point the well is not producing any revenue, and the abandonment procedures cost. The problem is exacerbated in the USA where the structure of the industry allows the well to be sold to a different operator. Such sales will frequently happen, and when the well is abandoned it can be owned by a small company that has nothing except that single well as an asset, so it simply declares bankruptcy and walks away, leaving an environmental problem.[50]

Technically, abandonment usually requires recovering as much of the casing as is practicable, and then filling some or all of the well with concrete. Just as in the drilling of the well, the integrity of the cement is critical, and for the same reasons.

Discussion

As the fracturing technology began to be widely used in the first decade of this century, there were many debates about whether this was an environmentally hazardous technology. Much of the discussion, particularly in the first years, has been about water, both with respect to

[50] Confirmed in personal conversations with small operators for Northeastern Pennsylvania.

quantities of water needed, and to water quality due to additives. Additional environmental issues include air pollution, noise and light. Table 5-3 lists areas of environmental concern, with Table 5-4 showing activities which raise environmental concerns. Part of the environmental awareness was probably due in part to the fact that the

Table 5-3 -- List of major environmental concerns in fracking activity. Modified after Rivard et al., 2014

Environmental concerns	Activities and comment
Sufficient water quantity	Siting; is there sufficient water for fracturing?
Water contamination	From pad construction through abandonment, contaminated surface runoff and/or aquifer damage are possible
Management of fracking and flowback fluid storage and disposal	Fracturing additives cause concerns
Solid waste disposal	Cuttings from drilling require proper disposal
Nuisances (noise, trucking, light)	Actual drilling is noisy, and 24/7 operations require well-lit working areas; compressors running throughout production phase may also create a noise problem
Atmospheric emissions / air quality	Throughout well life, dust from truck traffic and stray gasses from production operations; during drilling and fracturing, emissions from large diesel motors
Habitat destruction	Pad siting; roads and pipeline rights-of-way
Induced seismicity	Possible from fracturing operation, but primarily a problem associated with waste water disposal during production

Modified after Rivard et al., 2014

Table 5-4 -- Fracking activities which raise environmental concerns. Modified after Rivard et al., 2014

Primary activities	Environmental concerns and comment
Pad construction	Habitat destruction; modifications to natural drainage
Drilling	Noise, light, disposal of cuttings
Fracturing	Toxic additives: both handling and disposal; noise
Completion (except fracturing)	Proper disposal of tested hydrocarbons and drilling fluids; noise
Production	Noise; disposal of produced water; disposal of unsold gases
Pipelines	Habitat destruction; noise of pumps and compressors
Abandonment	Maintaining isolation of toxic sub-surface products from surface and near-surface environments

initial fracking plays, the Bartlett Shale in northeast Texas and the Marcellus area in Pennsylvania, are more densely populated than much of the USA, as can be seen in figure 5-5. As noted above, fracking requires many closely spaced wells so public awareness and impact was higher than in many more traditional hydrocarbon areas.

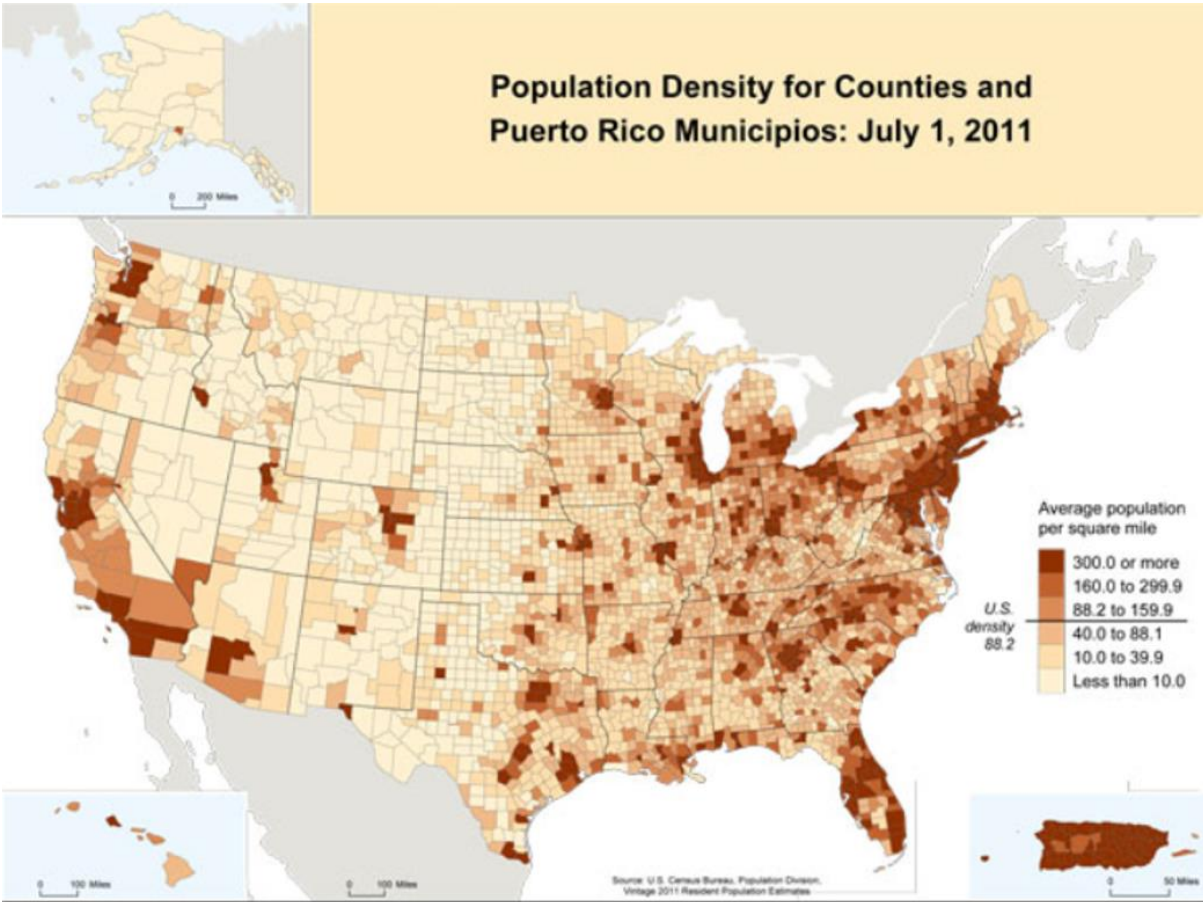

Figure 5-6 -- Population density of the USA, highlighting areas of early fracking activity (modified from US Census Bureau, 2011)

Also, many who were concerned about CO_2 emissions and global warming were pinning their hopes on "peak oil" forcing a decrease of these emissions (Kharecha and Hansen, 2008; Hall and Day, 2009; Hubbert, 1981), particularly because there was no political will, especially in the USA, to address the CO_2 and related climate issues.

In the discussion that follows it must always be remembered that the earth is heterogeneous; actual samples of the subsurface are obtained through a narrow well opening (frequently 8-inches (20 cm) in diameter) at a distance of 1 to 5 km (3,000 to 15,000 feet) from the well head. The models of the strata and the detailed nature of the hydrocarbon-bearing rocks are generally correct and useful, but the reality is more complex in detail.

Water

Water has received the most attention in environmental concerns about fracking. There has been some concern about the amount of water needed for drilling and fracturing, but by far the greatest concern has been about possible contamination of drinking water supplies, from surface water sources and especially from groundwater sources.

The initial geologic exploitation using widespread fracking took place in areas with adequate water supplies.[51] As noted above, the amount needed to drill and fracture a well can range from 2,000 m^3 to over 100,000 m^3 (0.5 to 26 million gallons or 1.6 to 80 acre-feet). Initially water is needed in the drilling of the well, and even more is needed in fracturing. But even where amounts of water are generally adequate, other water users need to be considered, often requiring permits (Hoffman, 2011). In more arid areas, notably the Bakken play and Permian basin play, costs increase, and water becomes part of the economic calculation that determines whether a well is worth drilling (Walton, 2019). In the Bakken play in North Dakota water for all mining activities (of which hydraulic fracturing is one) is less than 20% that of water used for agriculture (irrigation plus livestock) (Dieter et al., 2018). All of these factors mean that the water has a cost; because water is always produced along with oil and gas,[52] recycling of this produced water may be more economic than acquiring new water for operations (Walton, 2019). Moving all this water around requires either many trips of large tanker trucks or pipelines. Either method can result in accidental spills.

Particularly as it was being introduced, the hydraulic fracturing technology was widely referred to as “slick water” fracking, making it clear this wasn’t the same as the water coming out of the tap at the kitchen sink. Operating companies have not been successful in allaying the perceptions of risk. The US Clean Water Act partially removes EPA jurisdiction for waters used in fracking; this “Halliburton loophole”, which exempts most chemicals in fracturing fluids from US Federal regulation under the Safe Water Drinking Act, is an illustration of how perception of risk can become more important than actual data-based determinations of risk (Sidortsov,

[51] The Barnnet play in northeast Texas, the Marcellus play in Pennsylvania.
[52] Termed “produced water” in the industry.

2014). In Texas, questions related to drinking water quality are normally under the purview of the Texas Commission on Environmental Quality, but if an oil or gas well is involved, the water quality issues are under the jurisdiction of the Texas Railroad Commission, which is the state's oil and gas regulator (Meadows Center for Water and the Environment, 2015).

A primary concern has been the safety of drinking water supplies. The World Health Organization publishes guidelines for drinking water (World Health Organization, 2017); in the USA the Environmental Protection Agency sets legally enforceable limits for 90 possible contaminants (US Environmental Protection Agency, 2015) but some of the chemical additives and subsurface constituents may not have an assessment for a safe level (US Environmental Protection Agency, 2016). While the EPA standards are legally enforceable in the USA, there are numerous legal issues surrounding enforcement because regulatory monitoring is done at the state level.

Many states incorporate reporting to the FracFocus database, mentioned earlier (https://fracfocusdata.org/), as part of their regulatory requirements. But on its own, this industry database has limitations from a regulatory viewpoint (Maule, 2013). Shortly after FracFocus was set up, a study at the Harvard Law School (Environmental Law Program, Harvard Law School, 2013) outlined a number of these problems. Some of the criticisms raised in the Harvard study have been addressed by FracFocus since 2013, but there remain problems. For example, the number of chemicals not identified because they are 'proprietary' has actually increased recently (Trickey et al., 2020). There is a danger that when states require companies to report the composition of fracturing fluids to FracFocus, states may feel that this is sufficient regulatory oversight, but an industry database can only support government regulation and enforcement – it cannot supplant government functions (Trickey et al., 2020; Holley et al., 2019). The substances added to drilling mud are not generally controversial, but those added to fracturing fluid are, despite being a small percentage of the total volume. The largest single additive to fracturing fluid is 'proppant' – either sand or ceramics which will hold the fractures open after the pressure is released. These proppants are chemically benign. But the final additives, a mixture of organic and inorganic chemicals, while seldom more than one percent of the total fluid are frequently toxic. And despite the low percentage they still amount to thousands of gallons for each well. The specific chemicals used will depend on the chemistry of the rock being fractured; in addition, chemicals are added to reduce friction in the water itself,[53] as well as chemicals to prevent algal and bacterial growth in the well, and inhibit corrosion (Meegoda et al., 2017).

The hazardous chemicals have several routes by which they may enter the environment. There can be accidents in which concentrated chemicals are released directly prior to being mixed and diluted for final use. When the well is 'fracked' the mixture containing chemicals is pumped into the well under very high pressure. As discussed above, where contamination has been observed it is almost always the result of some problem with the well construction. A significant problem is that there have been water pollution problems in the USA for centuries, and when contaminants are found in analysis it can be difficult to determine whether fracturing fluids are the specific cause (Lambert, 2016). Today, many operators, if only to protect themselves in eventual legal actions, routinely test all water sources prior to drilling in an area.

Initial concerns were that the pressure of fracturing would force some of the fracturing fluid up through the rock column and into aquifers. But the most likely aquifer contamination problems come in the other direction; they arise from surface contamination, followed by 'well integrity' problems, usually a problem with the cement. Spills at the surface of either additives to the fracturing fluids or from flowback and/or produced waters constitute the bulk of aquifer contamination. Unless tightly contained, such spills can seep down into aquifers and disperse over significant areas.[54] But the populations in areas of fracking are frequently dependent on relatively shallow aquifers for domestic water (Grönwall and Danert, 2020). If an aquifer becomes contaminated, it is extremely difficult to de-contaminate it (MacDonald and Kavanaugh, 1994). These concerns were exacerbated by a faulty cement job in an early

[53] Hence "slick water frack" as the initial description of the fracking technology was frequently termed.
[54] This is not unique to spills from fracking; there are many large and very many small groundwater contaminations going back for more than a century due to leakage down from the surface.

Marcellus well near Dimock, PA, which the film *Gasland* used as evidence of generic problems.[55]

The critical book *Amity and Prosperity (Griswold, 2018)*[56] documents other problems with chemical contaminants in fracturing fluids. One of these is that when a company is sued the resolution is frequently an out-of-court settlement that includes non-disclosure clauses, preventing important data from public scrutiny. *Amity and Prosperity* documents the many difficulties in unambiguously tracing contaminants. These include background levels which may be high due to either natural or non-fracking causes (Engelder, 2018 (preprint)). In a specific instance from *Amity and Prosperity* book, contaminants may have been transferred from water to the atmosphere when aeration was routinely used to prevent algae growth in holding ponds, thus contaminating the air in the vicinity with a toxic mist (Griswold, 2018, p.80). By changing the problem from one of water pollution to air pollution, this complicated jurisdiction and regulatory issues.

The result of these concerns have been numerous, rigorous studies of water quality in areas of fracking (Vengosh et al., 2020 and Concerned Heath Professionals, 2019). Critical to interpreting the results of analyses with respect to fracking is having comparable analyses from the time prior to fracking operations. Initial complaints frequently did not have such comparative analyses; more recently it has become standard practice in most areas to do pre- and post-water quality analyses to determine whether fracking is the cause of water quality problems.

Disposal

A major water quality issue in fracking is what to do with the water that returns to the surface. Initially this will be flowback of the water used in fracturing, containing many of the chemical additives used. Compounding environmental issues is that additives to the fracturing fluid may react with the subsurface strata, thus changing its chemical composition (Kahrilas et al., 2015). Inorganic constituents

[55] As cited in note 18, there was an initial finding of a faulty cement job with the operator initially being ordered to provide imported potable water, and eventually deciding to purchase the properties affected. The final judicial determinations were inconclusive see M.C.Carlson (Magistrate Judge) (2017) Ely et al. v. Cabot Oil & Gas et al., Civil No. 3:09-CV-2284. Available at http://media.philly.com/documents/Memorandum-Opinion0331.pdf (accessed 2020-04-09).

[56] This well-written book was awarded the 2019 Pulitzer prize for General Non-Fiction.

of the fracturing fluid may react with clay minerals causing the characterization of the dissolved salts to change. As hydrocarbons are produced, the composition of the water coming from the well changes to that of the water that is virtually always present at depth. Whether in flowback water or produced water, some of the chemicals are harmful to health.

Proper treatment of this flowback or produced water (FPW) is critical. Removing dissolved constituents from water is always difficult (as every cook who has over-salted a dish knows), although the cost of doing so may be offset if the water can be re-used for further fracturing or irrigation (Walton, 2019). Although no longer permitted, operators in Pennsylvania used to send FPW to municipal waste water treatment plants; now they must use industrial waste-water treatment plants which can better handle these waters (Hurdle, 2016). Reuse of water is frequently cost-effective. As a result, operators now reuse this water when possible in new wells they are drilling in the area.[57] The other option is to use waste disposal wells to bury the waters at great depth. Use of waste disposal wells is discussed below in conjunction with seismic activity.

Treatment of FPW has significantly improved as fracking has become a widespread activity. Nevertheless, environmental monitoring of treated effluents has shown the presence of amounts of non-natural water constituents. Some of these may be toxic, others radiogenic, and some may be problematic simply because they are not natural. An example of the benign but non-natural constituents are dissolved bromine salts because they react with a standard treatment used for municipal water supplies downstream to create toxic chemicals in the treated water (Parker et al., 2014; Warner et al., 2013); this can force downstream communities to switch to more expensive treatment methods.

The Marcellus play in particular is noted for having high concentrations of radioactive salts in its FPW. In treated effluent, dissolved radium may be well below a danger threshold, but because the dissolved radium will tend to sorb onto clay minerals in the stream bed, the stream bed may become a low-level hazardous waste (Warner et al., 2013). Another natural process that can concentrate low levels of dissolved toxic material in wastewater is organic metabolism. Organisms can become toxic simply because they live in low-level toxicity. The classic example is swordfish, which have become contaminated with mercury (Torres-Escribano et al., 2010); a

[57] The nature of fracking is that wells have a rapid decline in hydrocarbons produced, so additional wells are frequently being drilled.

recent study has shown that fish living in streams of treated FPW have abnormalities (Papoulias and Velasco, 2013).

During production, FPW is separated from the commercially valuable hydrocarbons. But some hydrocarbons always remain dissolved in the water. Depending on the hydrocarbon chemistry of the geologic formation being exploited, these dissolved hydrocarbons may be more or less problematic. Most studies have shown the majority of the dissolved hydrocarbons in FPW are saturated, which carry lower health risks than aromatic hydrocarbons (Maguire-Boyle and Barron, 2014).

While waiting to be reused or transported for disposal, FPW will be stored either in tanks or open pits. Either way, unless it is used on the same pad, it will need to be transported. If the transport is to a nearby pad, this may be done by temporary, above-ground pipeline. Otherwise tanker trucks will be used. Either way there is a chance of spills, either from the storage tanks, or during transport. A North Dakota spill was of 3 million gallons (ca. 11 thousand m^3). The news report stated that “this flowed into the Missouri River, where it was quickly diluted to well below harmful levels” (Arnaud, 2015).

When storage is in open pits they are lined with heavy-duty plastic to prevent any seepage into ground-water. An obvious concern is that the plastic lining may develop a leak either through tears or normal wear. The water in an open pit must be kept free of algae in order to make it re-useable. One common method is to use sprinklers to aerate the water.

Cement

Cement is used during the construction of a well to isolate the final well bore from the surrounding rock. This isolates the hydrocarbons flowing to the surface from the surrounding rock layers. As illustrated in Figure 5-4, this may be done in multiple stages. Well integrity is defined as preventing any uncontrolled release of fluids during the life of the well (Standards Norway, 2013). As petroleum engineer Claude E. Cooke Jr. has commented “if there is a problem, the issue is well integrity”, going on to explain that the most likely cause is faulty cement (quoted in Gold, 2014, p.271).

Cement is a complex substance, and books have been written on its use in oil wells (amongst many: Lavrov and Torsaeter, 2016; Nelson (ed), 1990). Two aspects of cement are critical with respect to wells: it shrinks slightly as it sets and the setting reaction is exothermic. The slight shrinking can result in microscopic cracks between the cement and the casing, between the cement and the surrounding rock, or within the cement itself. The temperature changes as the cement sets can be another cause of microscopic cracks forming, either due to thermal expansion and contraction, or because the adjacent casing will expand and contract differently. Finally, the chemical reaction when cement sets is never really complete, and can continue so long as there are water molecules available (Lewis, 1992). Gas is more likely to seep through the resulting microcracks than liquids, but any fluid flow has the possibly to degrade the cement. The greatest concern with such microscopic flows is that the fluid, especially gases, from the hydrocarbon horizon will reach the surface outside of the equipment designed to process and control them (King and King, 2013). Other concerns are that fluids may not reach the surface, but instead contaminate aquifers used for drinking water (King and King, 2013). Bad cement can also provide a channel for gas or liquid to migrate from one intermediate stratum to another (US Environmental Protection Agency, 2016). Figure 5-7 illustrates this problem. The long lateral well segments typical of fracked wells mean that when cement is used around these sections, gravity may cause the fluid cement to distribute unevenly. This can result in a weak zone along the top of the annulus (Skadsem et al., 2019). Note in figure 5-7 that escape from the well environment can be into any overlying stratum, including shallow drinking water aquifers.

Cement also is critical when a well is abandoned. What is usually done is to fill at least both the bottom and topmost portions of the well with cement. But as mentioned above, the chemical reaction for cement is never totally complete. Although in the abandonment process the cement is presumed to last eons, if not forever, there will always be some risk that the abandoned well provides a vertical pathway through the rock strata. Thus, abandoned wells continue to present at least some risk to the environment (Rabia, 2019).

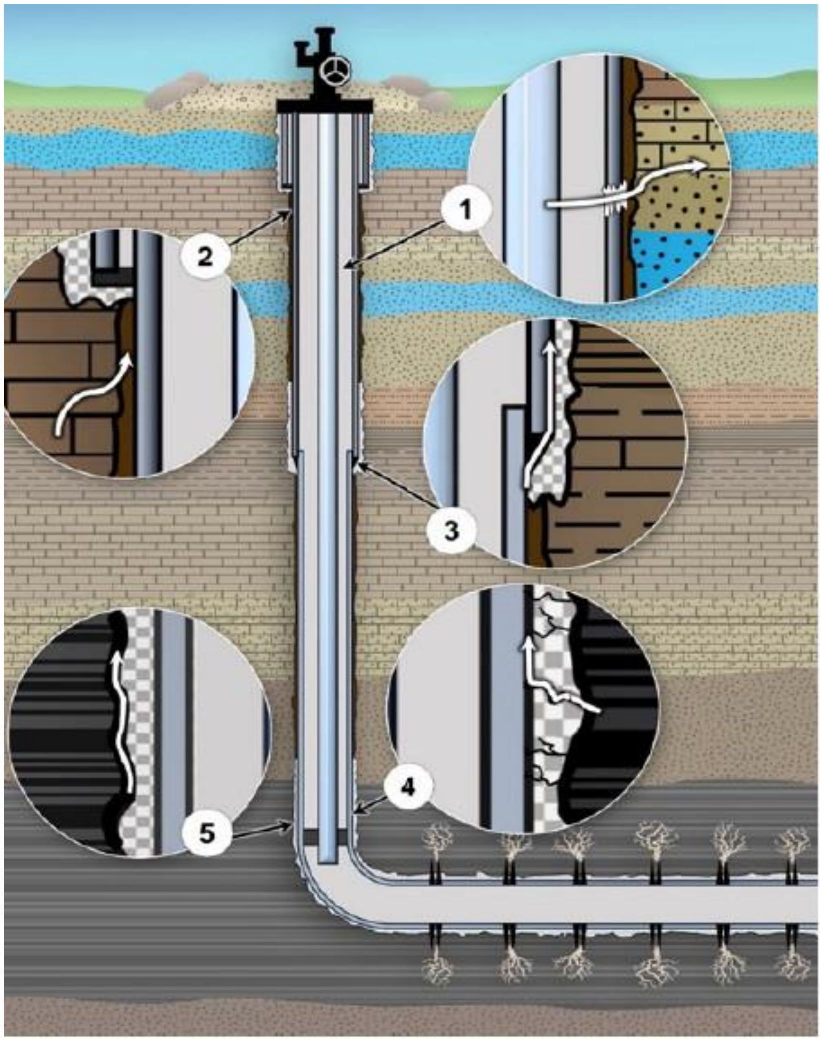

Figure 5-7 -- Possible contamination paths from well integrity (primarily cement) problems (after US Envoronmental Protection Agency, 2016)

Air

During the drilling process, the well pad is a major industrial site (Allshouse, 2019). The largest environmental issue during this stage of operations is exhaust from the large diesel engines used to power the drilling and fracturing activities (Vafi and Brandt, 2016). Dust can also be a problem. At the well pad any dry chemical, including cement and proppant, can pose problems as they are mixed into mud or fracturing fluids (Esswein et al., 2013). More often, dust is a problem along roads due to the increased traffic needed to support drilling operations than at the actual well pad (Graber et al., 2017). Other air pollution problems include aromatic hydrocarbons used as additives in the fracturing process, with at least some evaporation occurring during transfers from tankers to storage tanks and during mixing with the fracturing fluid. Aromatic hydrocarbons are frequently carcinogenic (Boffetta et al., 1997).[58] Evaporation can also occur from flowback fracturing fluid (McKenzie et al., 2018).

Once a fracked well is in production, the mixture of volatile hydrocarbons will need to be separated from fluids and either sold separately or disposed of. When the economic justification for a well is oil, then all the gases are extra. Traditionally they have been flared; this reduces the risk of pollution by various hydrocarbon constituents while increasing CO2 emissions. Natural gas flaring can be avoided by selling the gas as an additional hydrocarbon product, by using it in oil extraction operations, or disposing of it through injection into non-productive geologic strata. But selling the gas requires a pipeline, which may not be available in the area; unlike oil, gases are difficult to transport by tanker.

One of the issues in oil producing plays is that the economics of the well demand that it produce and sell the liquids it produces as quickly as possible. All of the operators in the Bakken and Permian Basin, which are two of the largest oil producing frack plays, would like to also sell gas, but they cannot due to lack of pipeline capacity; delaying production until pipelines are available threatens the economic viability of the well. After a delay and some public outcry, North Dakota (the bulk of the Bakken play) has introduced more stringent regulation for flaring (Ehrman, 2014). Texas and New Mexico (the Permian basin play) are rushing to build needed gas pipelines (Dix et al., 2019).

Flaring is not a perfect solution for disposing of unwanted gas. The bulk of the flared gas is methane, which can be explosive when the concentration in air is correct (Engelder and Zedenbergen, 2018). But released unburnt, the methane is quickly diluted by air to being only a trace constituent, so flaring for safety is required only near the source of release. Another safety reason for flaring is that hydrogen sulfide (H_2S) is frequently found in both oil and gas

[58] Hydrocarbons are divided into two major categories : aliphatic and aromatic. Natural gas (entirely) and crude oil (primarily) consist of aliphatic hydrocarbons; solvents and many manufactured organic chemicals are aromatic.

accumulations, and this gas is extremely toxic. H_2S safety is a concern in all petroleum operations, and flaring is often required to eliminate it (Skrtic, 2006).

The products of any flaring operation are complex, with many of them being toxic, corrosive or both (Ismail and Umukoro, 2016). Notable is some incompletely oxidized carbon, resulting in CO rather than CO_2. Any H_2S burns to create H_2O (water) plus SO_2 (sulphur dioxide, a gas), which together are sulfuric acid. The burning reactions can also produce various nitrogen compounds, NO_x, which cause smog and have other problematic issues.

The fracking boom has been responsible for a significant decrease in USA's CO_2 emissions. This is due to a switch from coal to natural gas in many applications, notably electricity generation. Burning natural gas releases more energy per unit of CO_2 emitted than burning coal (EIA; 2020; Howarth et al., 2011). The basic reason is that coal is essentially pure carbon, so the chemical energy is obtained by combining the carbon with atmospheric oxygen; when natural gas (close to pure methane) burns, the energy comes not only from carbon but also from the hydrogen.

Methane

While using methane as a fuel has CO_2 emission benefits, methane itself, i.e., unburned, is a much more potent greenhouse gas than is CO_2 (Yvon-Durocher et al., 2014). For the fracking plays that are exploiting gas, there are concerns that much of the benefit of switching from coal to natural gas is offset by methane leakage throughout the path from producing well to final user (Howarth et al., 2011). Some of these leaks date back to infrastructure originally put in place for "town gas" more than a century ago (von Fischer et al., 2017), but some can be directly attributed to natural gas production from fracking plays.

Atmospheric methane concentrations have been increasing recently with the result that its sources have been the subject of recent research (Nisbet et al., 2016). The increases in atmospheric methane data can be traced to increased oil and gas production over the past decades, despite the fact that methane released per unit of production has decreased (Schwietzke et al., 2016).

Traffic

One of the major environmental issues during well pad construction and continuing through the drilling and fracturing operations is the amount of heavy truck traffic required to support the operations. As illustrated in figure 5-3, secondary and specially constructed roads are often used; frequently these are unpaved. Even when load and speed limits are strictly observed, the amount of traffic and weight of trucks may require frequent maintenance of roads across the area of a play compared to pre-fracking maintenance schedules.

Table 5-5, drawing on data from an environmental impact statement, gives the estimated number of heavy truck trips needed to support a single well. In 2012 the deputy director of the Texas Department of Transportation was quoted “We need $2 billion, and the shortfall is

Table 5-5 -- Heavy truck trips per well (after Abramzon et al., 2014)

Well stage	N. of truck trips
Pad preparation	45
Drilling	235
Fracking	258 to 698
Completion	70
Production	45 to hundreds
Abandonment	(not estimated)

$2 billiion” (Shlachter, 2012) when discussing the road maintenance needed to support fracking. Several factors compound the problem of road maintenance. When an operating company makes a road improvement the costs are capital expenses which can be financed against projected revenue, whereas for governments these are maintenance costs which must be currently financed. In addition to a timing mis-match, there is frequently a jurisdictional mis-match between the jurisdiction responsible for the costs and the jurisdiction that, eventually, may collect tax revenue. “Road Use and Maintenance” agreements may help, but seldom cover all of the costs involved (Abramzon et al., 2014).

Road use is an issue during pad construction, but as table 6-5 shows, the major road use issues are during drilling and fracturing. In addition to road maintenance, road use raises environmental issues along all the roads used of noise and air pollution due to exhaust and dust. Dust can be a major issue when roads are not paved. On all road surfaces, traffic creates fine particle pollution, with microscopic tire wear and exhaust soot being major components (Wik and Dave, 2009). Furthermore, cars and trucks create noise. There is the noise of the engine plus the noise created by the tires on the road surface (Wei et al., 2016). And, because drilling and fracking is a round-the-clock operation seven days per week whatever traffic noise there is will be unceasing. This has led to particular problems where a quiet home has been purchased for retirement on a small country road that suddenly becomes a busy highway (Engelder, 2013).

Land use

The fracturing process enhances permeability next to the well bore. But unlike exploitation of conventional, more permeable accumulations, fracking plays require a very large number of wells to collect the hydrocarbons stored in the rocks. Figure 5-8 shows the density of wells in a portion of northwest North Dakota. Although drilling clusters of wells from a single pad reduces the land surface footprint, the number of wells required still means that pads in a play will dot the landscape.

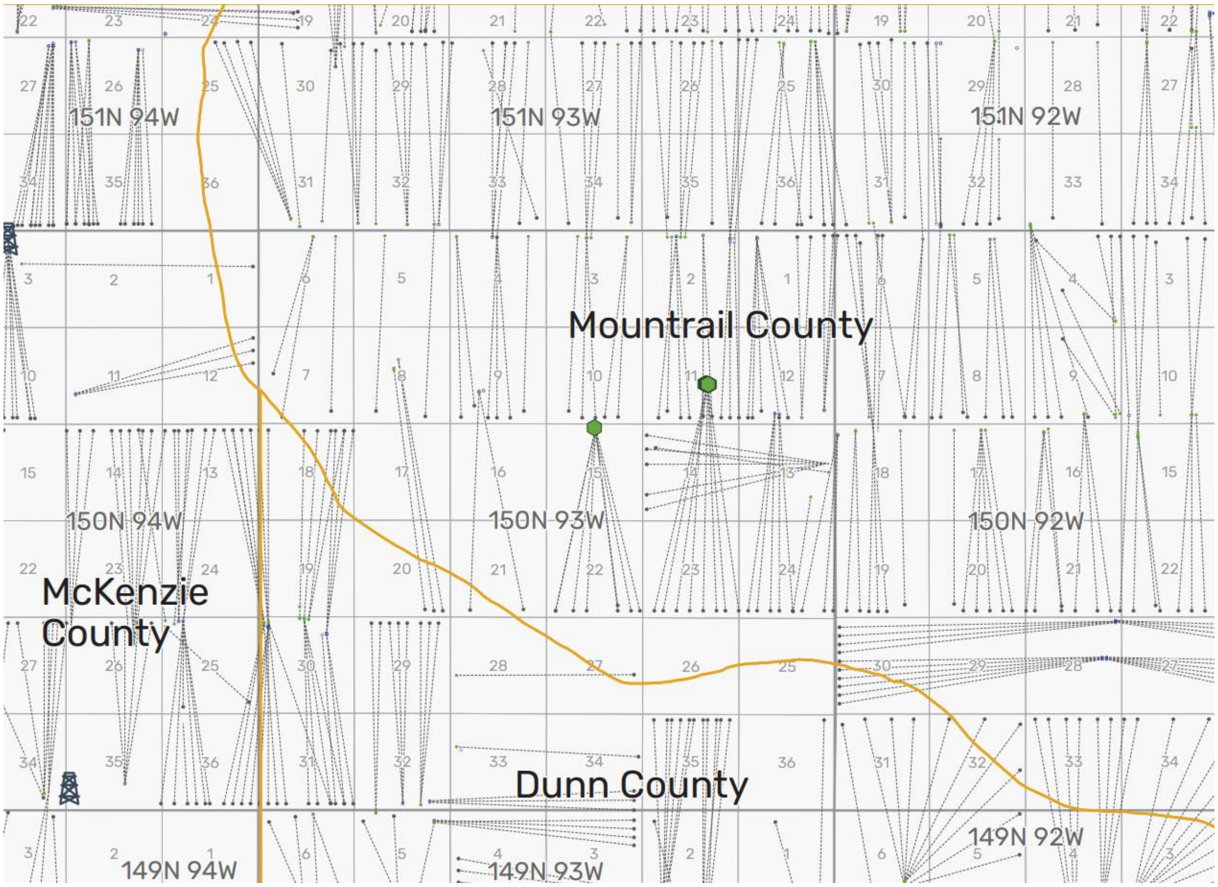

Figure 5-8 -- Well traces in northwest North Dakota (Hart Energy, 2020)

In addition to the pads, access is needed for each pad, including roads, utilities and eventually pipelines. For the environment, roads and pipelines are a major break in habitat. For example, some species of woodland birds are not found within 300 feet of the woodland edge; while a road or pipeline right-of-way may use very little of the land surface, say 5%, they may destroy an ecology by creating paths, and therefore edges, within large tracts of woodland (Porensky and Young, 2013). Similar issues can impact wetlands.

Fragmentation of rights

Specific to the situation in the USA, private ownership of mineral rights makes the siting of pads more difficult. The fact that surface ownership and mineral rights can be severed compounds these difficulties. Operators spend many hours researching ownership, sometimes having to trace intestate ownership through several generations, which can be costly. Furthermore, the mineral rights carry, with some restrictions, the right to access the subsurface; this may give rise to additional issues.[59]

Social changes

The economic activity of developing a play with fracking can lead to social changes. Some of these can be for the better; a local landowner has said "ten years ago it was obviously an impoverished county; today the houses are painted".[60] Operating companies have funded improvements to local hospitals (Hiduk, 2018), and other local projects.

But the economic benefits have come with "boom town" problems. Formerly, one could transit Towanda, Pa., having to wait at most for one cycle of the traffic light; now the wait to get through the intersection can take 45 minutes.[61] More significantly, the uneven distribution of these benefits can lead to animosities. Neighbors no longer speak to neighbors; families can be torn apart (McGraw, 2011; Sinclair, 1926).

In particular, those who benefit from fracking operations: workers, the support economy, operators, mineral rights holders, will tend to be supportive; those who bear the costs: local property owners (through higher taxes), and users of public health facilities and other common facilities such as parks and a clean environment will skew towards opposition. And as noted specifically for roads, the tax structure is not designed to channel any monetary benefit of fracking to the government sectors and entities which are directly impacted (Samuels, 2018).

Health effects

An area of great concern is the health impact of fracking. A number of studies have directly addressed this issue (Hays and Shonkoff, 2016), Hirsch et al., 2018). One study has detailed the changes in health parameters before and after fracking activity in an area (Jacobson, 2019). Another study has shown that there are adverse effects of fracking in direct proportion to the

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[59] For example, see EQT Prod. Co. v. Crowder, 241 W.Va. 738. See write-up at https://www.propublica.org/article/when-fracking-companies-own-the-gas-beneath-your-land (accessed 2019-07-15).
[60] P.Flaherty (2015) personal communication.
[61] A resident's personal communication

distance from the pad (Currie et al., 2017). This peer-reviewed article has valid statistics, but isn't able to specify a cause. It could be noise pollution, air pollution, or possibly that increased royalties resulted in more economic ability to address medical issues. While difficult to assess, the noise of a drill pad may cause health problems (Hays et al., 2017).

Economic interests

All extractive industries are subject to a boom and bust cycle. The earth is finite, and extraction has limits, almost by definition. The economic benefits and problems accrue at different time scales, and frequently in different locations.

The land itself is changed by the extraction. Whether it is simply changing the topography slightly to construct a pad or a right-of-way cut through a forest, the changes to the land will be long-lasting. Abandoned wells are for fracking what abandoned open pit mines are to mining – changes to the landscape that will only be fully erased in eons of time to come.

On the positive side, the global economy requires energy. As many have pointed out, GDP is directly correlated with energy 'consumption'.[62] At present, over 80% of global energy comes from fossil fuels: 27% coal, 33% oil; 24% natural gas (BP Statistical Review of World Energy, 2020). This means that 57% of the global economy is dependent on supplies of natural gas and oil.

Fracking is expensive and has never been profitable across all operators (Foss, 2020). At present, several non-fossil-fuel energy sources are competitive for new supplies on a cost basis (Bentley et al., 2020). But two things make rapid change difficult. First, the economic system, particularly transportation, is designed around fossil fuels. Changing requires capital investment in different equipment, which may either require some write-off of existing (un-depreciated) equipment or incompatibilities with respect to operations; this is an inertia which works against change. Second, the remaining reserves of conventional oil in Russia and the Arabian/Persian

[62] We may have learned in secondary school the 'energy is neither created nor destroyed'. This is true; but "consumed" feels the correct word – gasoline doesn't unburn, so we have to keep filling up our tank. The reason is that energy goes from a concentrated to a diffused state; energy from gasoline to dissipated heat. See S.Carmalt (2017) *The economics of oil*, New York, Springer, 105p.

Gulf are not well known, but for a number of years can, on a technical basis, continue to undercut supplies produced by fracking (Auzanneau, 2020). Because these resources can be provided at lower cost, they undercut expansion of fracking to supply hydrocarbon energy.

Conclusions

A single well is unlikely to cause problems

A single fracked well, or even a cluster of wells on a single pad, are unlikely to be a major environmental problem. There is some surface impact, and a small chance of technical problems creating a large impact.

What all of the above documents, and what is more problematic, is that wells on a single pad won't exploit the resource, and many more pads and wells will be needed. Combined, this certainly increases the "footprint" on the land, and statistically a few of the wells will have significant environmental problems or accidents during the course of their productive life which have significant impact on the environment. Furthermore, while any single well or pad may be within regulatory tolerances, the thousands of wells drilled to exploit a play will have a cumulative impact, which the regulations don't address.

In considering the environmental risks, operators tend to cite the studies showing that there is low environmental risk from fracturing a single well whereas campaigns against fracking tend to cite the cumulative effects in developing the resources over an area (King, 2012). The result is a "dialogue of the deaf" because the two positions are talking about different things.

The resolution of the question "is fracking environmentally detrimental" is therefore not one that can be addressed solely as a matter of science. There is no yes or no answer. Rather, it requires a political discussion in which the benefits of fracking are weighed against risks and severity of the detrimental impacts. At present, particularly in the USA, such political discussions rely heavily on economic metrics rather than metrics derived from pure science.

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"Duff" Gold, and Mr. Patrick Mordovancy. The opinions expressed in this paper are solely those of the authors.

Chapter 6 -- Natural Gas Production in NE Pennsylvania

Production data in Pennsylvania is reported to the state by the operating companies, and is then made publically available[63]. Figure 6-1 shows the counties considered for analysis of NE Pennsylvania gas production in this report. Data for these counties was extracted from the

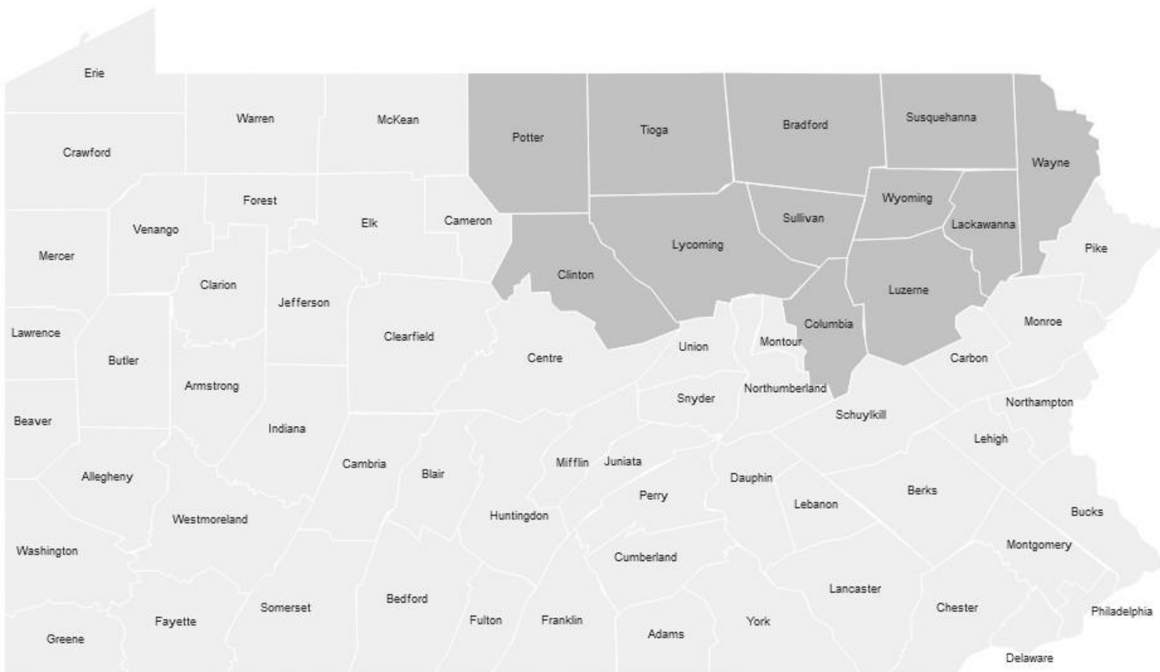

Figure 6-6-1 -- County production data used

larger data set by well permit number, considering only readable records, wells that produced gas, and those that were classed as 'horizontal' (as opposed to 'vertical'). The distinction between horizontal and vertical approximates the use of fracking technologies. Fracking of horizontal wells began in Pennsylvania in 2005 and greatly increased from about 2008. While the reporting is designed for monthly production data, many records consolidated multiple months, in which case the consolidated amount was distributed evenly over the months involved.

[63] Data is published by the Pennsylvania Department of Environmental Protection. Data used was downloaded from https://www.dep.pa.gov/DataandTools/Reports/Oil%20and%20Gas%20Reports/Pages/default.aspx on 2022-03-15 via a VPN link (the page is not easily accessible from outside the USA).

A Pennsylvania county is divided into townships and boroughs, the latter being settlements of sufficient size to warrant a local government when the areas were politically organized in the first decades of the 19th century. Townships were, and in NE Pennsylvania mostly remain, almost entirely rural. Because boroughs are of small geographic area the data for boroughs has been consolidated with one of its adjacent townships. Figure 6-2 shows all of

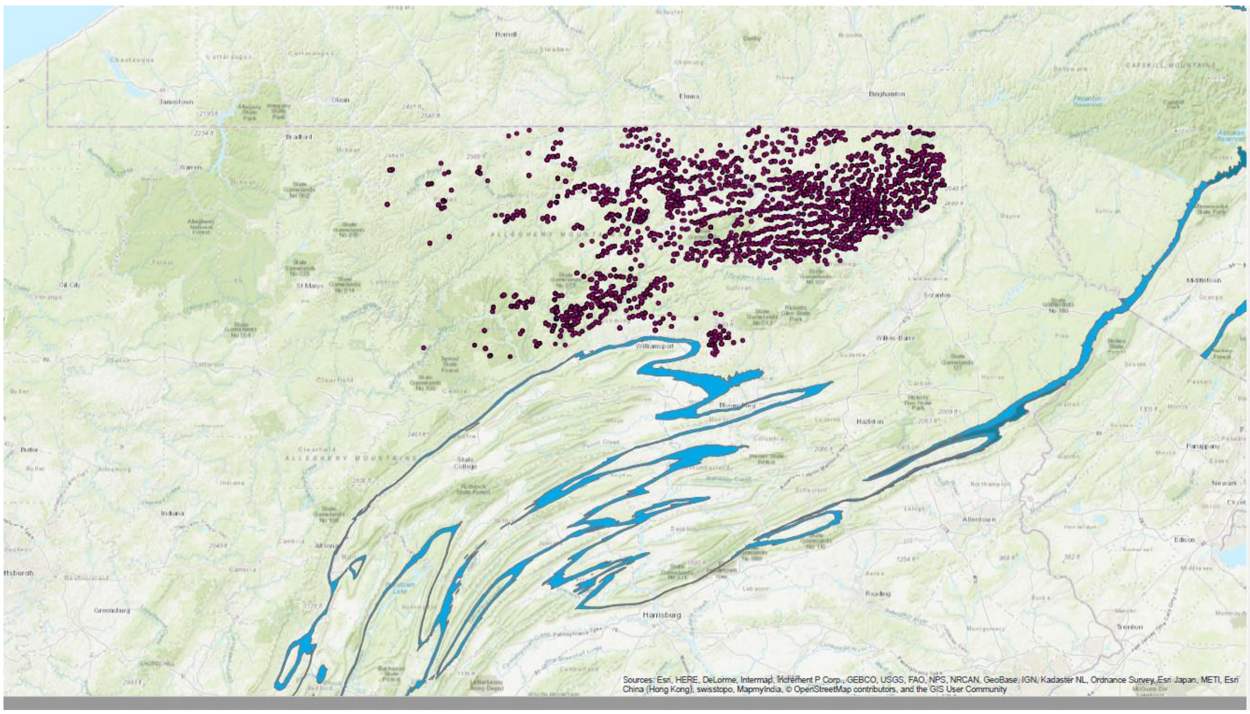

Figure 6-6-2 -- Horizontal gas wells drilled in NE Pennsylvania

the fracked, i.e. 'horizontal', gas wells drilled in the counties of NE Pennsylvania that have been used to examine the production patterns. Because the fracking technology of horizontal wells was only introduced into NE Pennsylvania in 2007, the data only begins then. No horizontal gas wells were found in the database for Colombia, Lackawanna, Luzerne or Wayne counties.

Production data prior to 2016 is problematic. For example, there is no data reported for the second half of 2015, and data prior to 2015 has noticeable gaps. But the data from January of 2016 onward are consistent and appear complete. Figure 6-3 shows total US gas production (EIA, 2023c) according to the major producing plays. The Marcellus production represents approximately 25% of total US natural gas production. For the Marcellus play figure 6-3 shows the production from the entire "play", which includes areas throughout Pennsylvania plus production from Ohio, West Virginia and Kentucky. Since 2016, the NE Pennsylvania component of Marcellus production has been just under 50% of all US

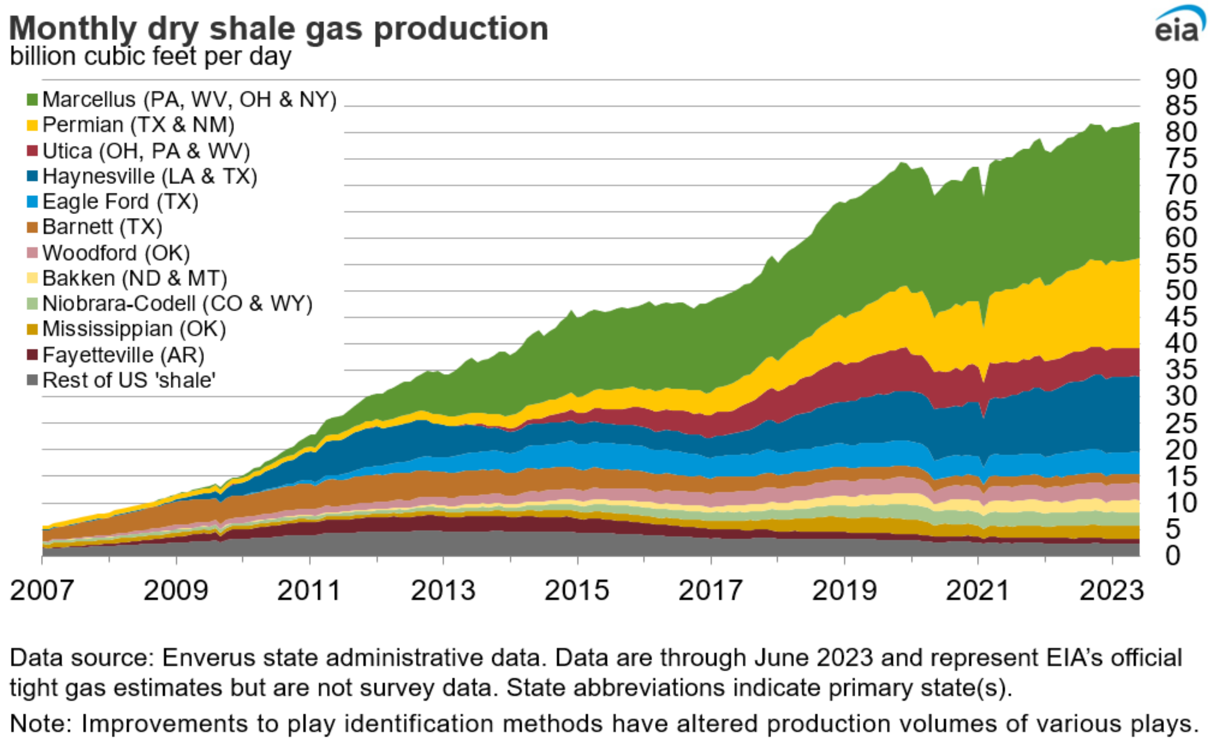

Figure 6-6-3 -- Dry gas production in USA (EIA, 2023c)

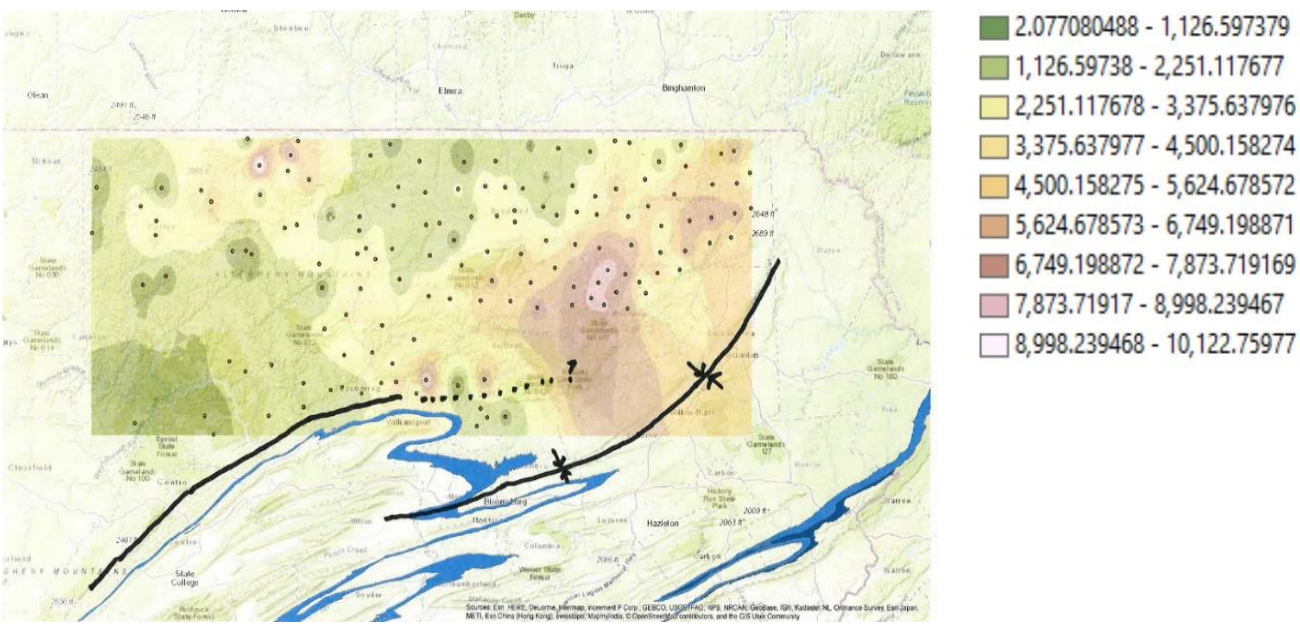

Figure 6-6-4 -- Average well productivity by township in NE Pennsylvania 2016-2021

Marcellus gas production. Figure 6-4 is a contour map of average well production by township in northeast Pennsylvania since 2016. Production data for each township has been summed and the totals divided by the number of producing wells in the township with the results then machine contoured, using the geographic center of the township as the location point for the data. A presumed extension of the Allegheny Structural Front is shown, as is the axis of the Lackawanna syncline, which contains Pennsylvanian aged anthracite coal. The contours seem to indicate that the limit of production is the extension of the Allegheny Structural Front. Stratigraphic sections that cross the Allegheny Front further to the southwest in Pennsylvania (Trippi et al., 2015) indicate that the Front marks a significant change in depositional history. One of the researchers compiling the stratigraphic section observed that when the Front was crossed from the Appalachian Plateau into the Valley and Ridge, “the bottom drops out” (Trippi, 2015, personal communication).

Fracked wells experience rapid declines

In assessing the future of gas production from NE Pennsylvania, the most important factor is that fracked wells have rapid production declines. Figure 6-5 shows the average production

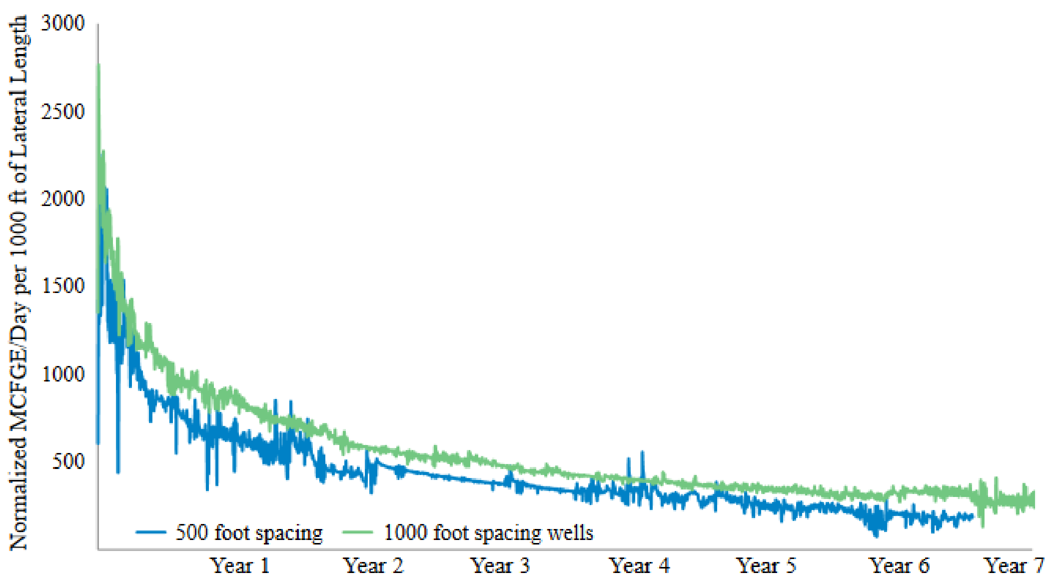

Figure 6-6-5 -- Production decline curves for Range Resources wells (after Higley and Enomoto, 2019a) profile for the wells of Range Resources, which exploits the Marcellus Formation in the SW part of Pennsylvania. Figure 6-6 is a similar decline curve for Cabot Oil & Gas (merged in

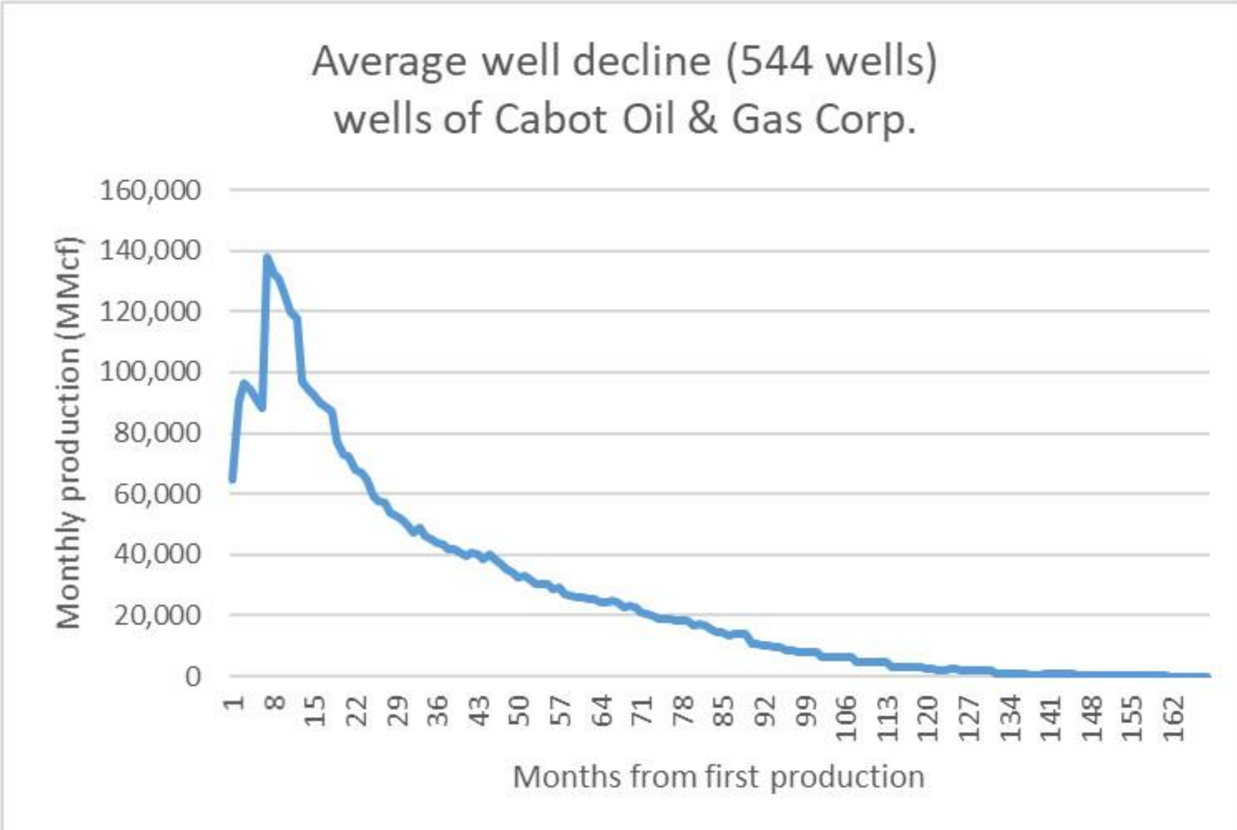

Figure 6-6-6 -- Combined decline curve for 544 wells of Cabot Oil & Gas Corp. in NE Pennsylvania

2021 to become part of Coterra Energy), which is one of the most active and successful operators in NE Pennsylvania. For each of the 544 wells included in the Cabot data, the production has been aligned to the month of first recorded production to give a composite well decline profile. The average decline is significant, with very little production per well after 10 years (120 months); production after only 5 years is generally less than 25% of the initial production rate. That fracked wells show rapid production declines has been a feature of the industry activity that have resulted from the fracking technology.

Of interest is that on a per well basis, the volumes produced from very close spacing of lateral wells in the Range Resource data is somewhat less than for the wider spacing. In NE Pennsylvania, typical spacing is 500 to 600 feet (Engelder, 2022 and Mordovancy, 2022, both personal communication).

Early in the fracking era the concept of “factory drilling” became fashionable. Briefly, this concept held that so long as new wells continue to be drilled in a “tight” play, the rapid declines of individual wells would be offset by production from new wells, thus allowing the overall play production to remain steady or even increase. Furthermore, this steady or increasing production would provide the revenue to allow continuing drilling and fracking of more “tight” oil and gas wells to continue, with sufficient surplus to pay down the initial capital investment. There are two fundamental problems with this concept:

First, the concept presumes that the territory in which to drill productive wells is limitless. But this is not true. In the case of the Marcellus in NE Pennsylvania, local operators (personal communications, 2022) note that no new pads are being constructed and all activity is now “infill” drilling of additional lateral wells from existing pads. In the case of Susquehanna County, 1722 gas wells have been drilled. New lateral wells are up to 3 miles long, with lateral spacing of about 500 feet; this is a horizontal area per well of about 0.736 km^2. With the county total area of 2,155 km^2, this means that 59% of all possible wells have already been drilled. This is obviously an approximate calculation, but it illustrates the limitation in projecting production into the future. This puts some significant limits to the future natural gas potential of the county.

Second, a drilling program will collapse financially rather than just slow down if there is a hiccup in cash flow. The reason is that the revenue from new wells is needed immediately during their high production phase to both drill the next well and amortize the remaining capital costs of all existing wells. Initial investments in “tight” plays in new areas thus were able to get programs started, but the on-going reinvestment requirement makes repayment of the initial investment difficult.

Many of the investors in the initial fracking activity, particularly those in the financial community, have been reluctant to continue their investments. Not only is this due to realization that the rapid production decline rates are causing repayment problems, but also because there is increasing ESG[64] pressure to wind down investments in fossil fuels as well as the fact that interest rates are now much higher than when the initial investments were made (Chancellor, 2022).

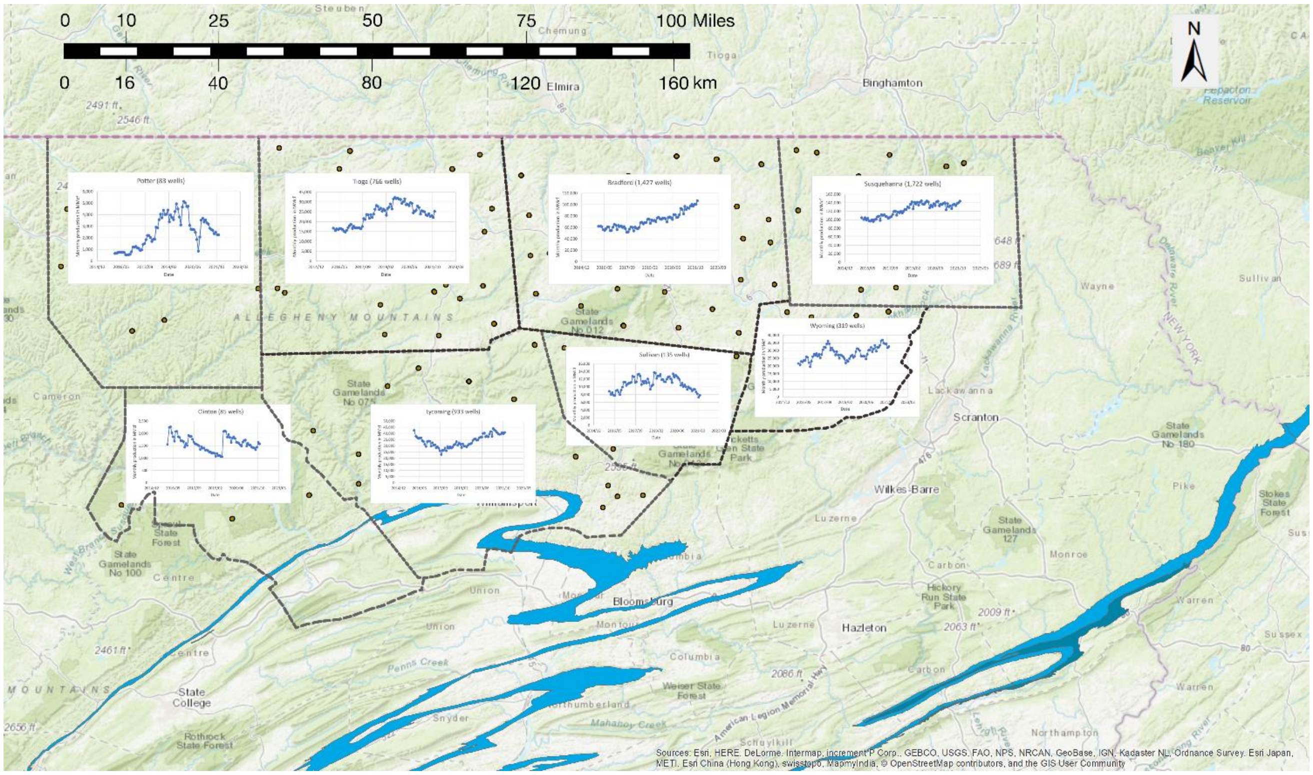

Figure 6-6-7 -- NE Pennsylvania production 2016 to 2021 by county. Data are in MMcf.

Figure 6-7 shows the gas production for NE Pennsylvania since 2016 by county. As of 2022 when these data were collected, only Bradford County shows increasing production. The

[64] ESG stands for Environmental, Social and Governance criteria. It's impact varies across companies and governments.

composite graph for the region in figure 6-8 shows only modest increases over the period,

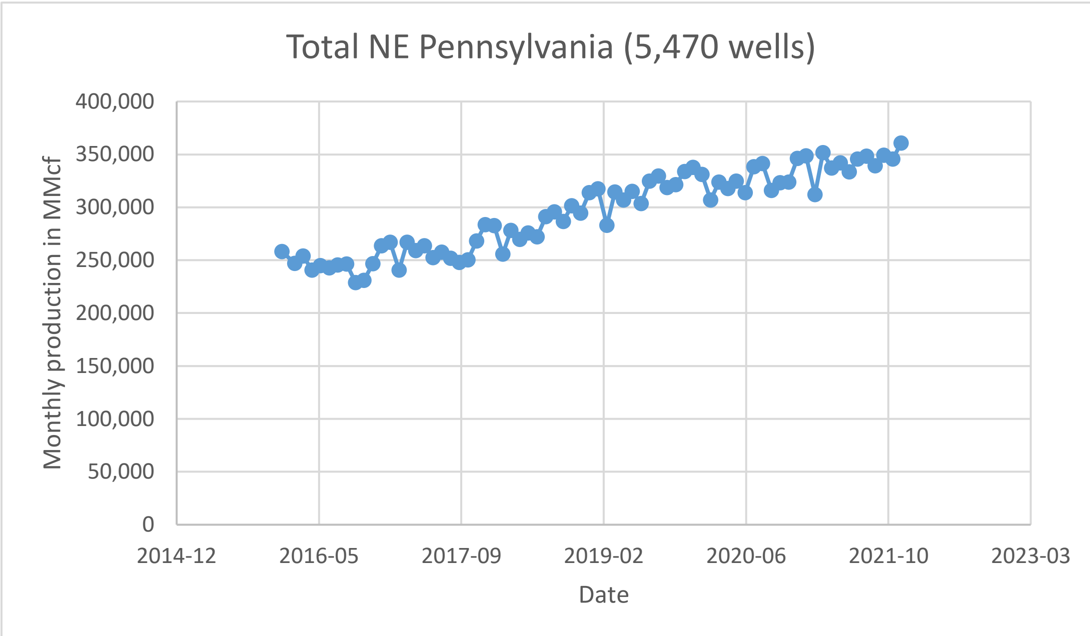

Figure 6-6-8 -- Natural gas production from NE Pennsylvania since 2016 and very minor increases over the past two years, despite the increases in Bradford County. More recent data from the US Energy Information Administration (EIA, 2023a) (figure 6-9)

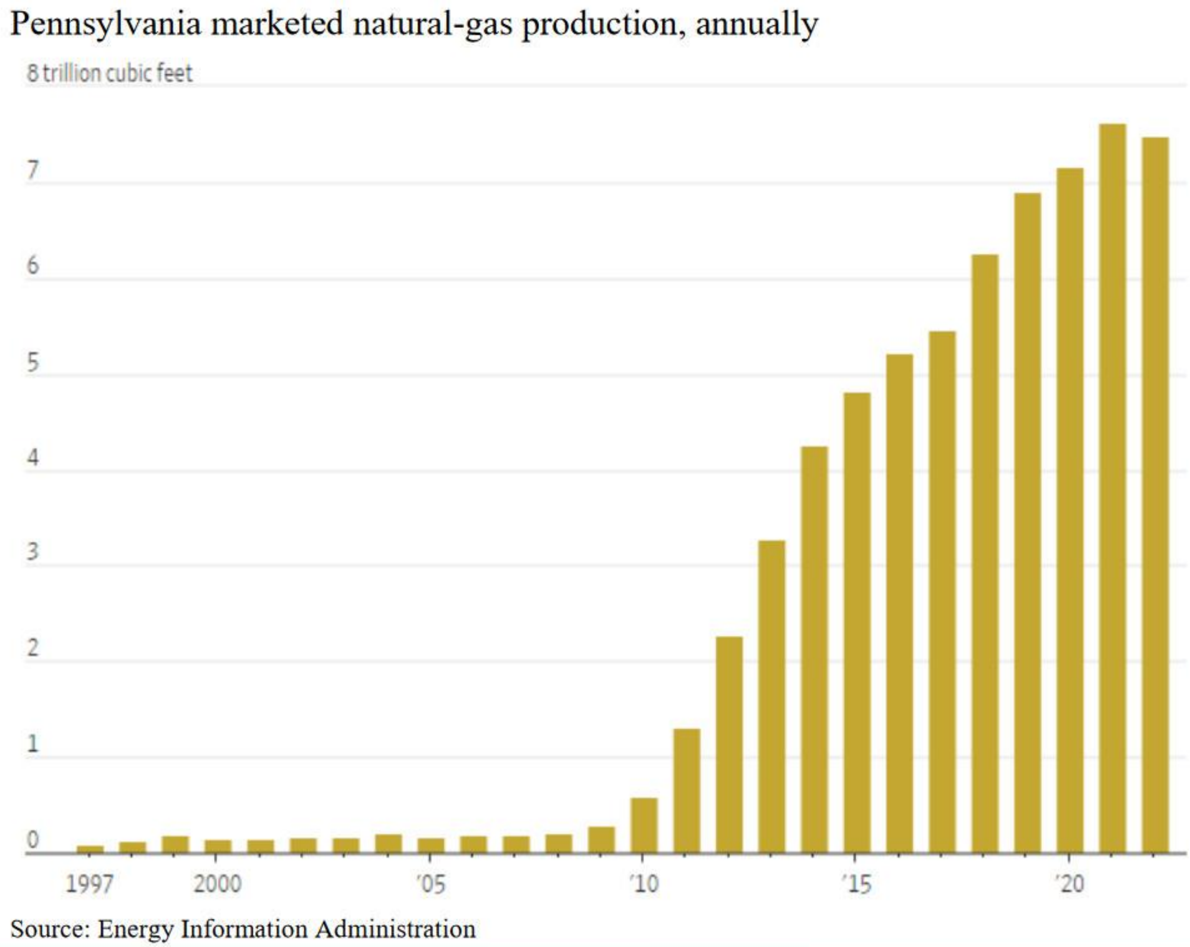

Figure 6-6-9 -- Total Pennsylvania natural gas production (EIA, 2023a)

indicates that Pennsylvania natural gas production actually declined slightly in 2022, although this data isn't perfectly comparable as it includes dry gas production from the entire state, and thus including some from formations that are not the Marcellus. The EIA discussion postulates that some of this decline may be due to the lack of pipeline capacity.

The data show that production from NE Pennsylvania is no longer increasing. There is no indication in any of the data that significant increases from the area are likely over the coming years.

Chapter 7 -- Discussion and Conclusions

Hydrocarbon resources exploited directly from shales present different exploration challenges from conventional oil and gas exploration. The 'source—reservoir—trap' trilogy of traditional oil and gas fields doesn't apply; rather, shale resources depend only on organic richness and thermal maturity of the source, which is exploited directly. From about 2000, the US Geological Survey has distinguished 'continuous' and 'traditional' hydrocarbons in its periodic resource assessments. This distinction is the result of the 'fracking' technology, largely developed in the 1990s, which allows direct exploitation of these continuous resources.

The Marcellus shale is one such continuous resource; primarily natural gas, with some light liquids in its western areas of Pennsylvania and in Ohio and West Virginia. Unlike traditional oil and gas resources, the importance of geology is somewhat less of a factor in exploitation of the Marcellus; frequently it is not even the most important factor. All exploitation decisions are made with reference to projected economic benefits. With continuous resources, the geology is roughly continuous across the entire area and other factors become important. Hence differences in the political situation, property ownership, surface locations, and local environmental constraints all become relatively more important in well siting and other exploitation decisions.

The Devonian Marcellus formation is organic-rich throughout its extent, and everywhere in Pennsylvania has reached sufficiently high temperatures needed to form significant methane (Higley and Enomoto, 2019b). In northeast Pennsylvania the resulting hydrocarbons are almost entirely "dry gas", that is, gas with almost all its C-C bonds broken (Laughrey, 2022). Indeed, the Marcellus formation is folded beneath the Lackawana syncline, where later (Upper Carboniferous) rocks have reached anthracite coal grade. While not accessible, the organic material in the Marcellus below the Lackawana syncline may have become graphite. When the maturity level has converted organic matter into fluid hydrocarbons, it is the impermeability of the shale itself that serves to trap them, and fracturing technology can exploit them.

The surface exposures of the Marcellus formation provide a means to characterize the formation. As shown in chapter 3, the organic carbon content is sufficiently high to make the Marcellus a source rock. But the surface exposures are in the Valley and Ridge province, where the organic material has been degraded by weathering. Despite the fact that stratigraphic control within the surface exposures sampled is not precise, the samples analyzed confirm that the most organic-rich part of the formation is that closest to the base. The physical sampling conducted for this study confirm the many other studies of the Marcellus shale (Engelder, 2014, Harper and Kostelnik, 2011a, 2011b, 2011c, Higley et al, 2019a, Kohl, 2012, Laughrey, 2014, 2022, Laughrey, C.D. et al., 2011, Milici and Swezey, 2014, Schmid, 2021, Soeder, 2017, Trippi et al, 2019, Wang and Carr, 2013, and Zagorski et al, 2012, 2017). Similarly, the inorganic matrix of the Marcellus as confirmed by X-ray analysis and QEMScan automated petrology is generally a mixture of quartz and clay, with the clay being primarily illite. The geological analyses undertaken in this study have served to confirm previous understandings of the Marcellus Formation.

The basic geology of the Marcellus has been known for more than 170 years, and the geologic insights from this work confirm rather than extend what is already known about the Marcellus shale. What this study does illustrate is that factors besides geology influence whether exploitation at a specific site is warranted; local political factors and landowner permissions are important, as are projections of the monetary costs and returns. Thus while some site selection is important when considering where to drill a well, the final decision is likely to depend more on details of engineering (e.g., site location, landowner permissions, road access) than the specific geology. One geologic factor that is relevant, at least on a regional basis, is the amount of clastic material in the shale (Wang and Carr, 2012); without sufficient clastics in the shale, it becomes too plastic to maintain the fractures which will allow gas to flow into wells. Another regional consideration is degradation by weathering; when the Marcellus has been weathered, the organic material has been degraded.

Organic material has been in the Marcellus since it was deposited 390 million years ago, with the burial to depths that resulted in conversion to gas was probably complete by 250 million years ago (Higley and Enomoto, 2019); the gas has been there ever since. Given that recovery factors for fracked exploitation are low, much gas will likely remain in the formation long into the future.

Despite all of the negative factors, the Marcellus has produced significant gas for the US economy over the past decade. Although exploitation by fracking started about 2008 (conventional hydrocarbon exploitation in the area goes back to 1859), the productive areas have made a major contribution to US gas supplies over the past two decades. When the study was proposed in 2015 the industry was incredibly optimistic about the resource – it was and is massive, especially the unqualified esimates by Engelder and Lash (2008a, 2008b). It is close to major markets, and there were high gas prices. There were initial hiccups in exploitation related especially to water contamination which slowed the pace. Then in 2014 oil (and therefore all energy including natural gas) prices plummeted, and what had been 'boom' economic activity ceased. Since then the activity has been almost entirely driven by the economics of various companies, a significant factor being the need to hold, via production, the acreage positions acquired during the boom period at high prices, thereby preserving at least some of the investment value.

Given the way the industry operates in most of the USA, which is different from most of the rest of the world, most of the mineral rights in the areas deemed productive have been acquired by various companies by the leasing of mineral rights from thousands of individual land owners. Many of these companies paid more that these rights were worth, and so there has been considerable merger and acquisition activity amongst the companies. To hold the mineral rights, the companies continue to drill wells. With infrastructure in place, it becomes economic to continue to drill 'infill' wells from the existing drill pads. But as shown in Chapter 6, the volume of the formation already exploited is reaching the 50% mark. Coupled with the rapid decline rates that characterize production from fracked wells, this suggests that significant gas production from NE Pennsylvania will diminish within the next 10 to 15 years.

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Appendix A – What is a Giant Field?

What Is a Giant Field?

Carmalt S. W., and Andrea Moscariello, 2017, What is a giant field?, *in* R. K. Merrill and C. A. Sternbach, eds., *Giant fields of the decade 2000-2010*: AAPG Memoir 113, p. 9-14.

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Abstract

Study of giant oil and gas fields is useful not only to understand oil and gas habitat but also because statistical analysis of these data sheds light on future energy supplies. In such statis- tical studies, the definitions of both “giant” and “field” are important. The development of giant accumulations that are not fields increases the resource supply but can simultaneously decrease the accuracy of resource estimates and production forecasts unless care is taken with definitional issues.

Background

This volume is the fifth in a series of AAPG Memoirs that focus on the giant oil and gas fields[1]. As Michel Halbouty correctly observed in his introduction to the first volume in 1970, the giants play a disproportion- ate role with respect to both hydrocarbon reserves and hydrocarbon production. And as Grunau (1983) observed, the giant fields frequently provide the best data available on what has been discovered. Because oil plus natural gas account for over half of the global energy supply (IEA, 2014), their contribution to theglobal economy is a subject of interest and commentary far beyond the science of geology. Inclusion of the un- conventional reserves and production from Canadian oil sands, and the continuous Bakken oil play and Marcellus gas play, have been cited for a range of opin- ions far removed from the science of geology.

Over the past two centuries, fossil fuels have be- come critical to the functioning of the economy. Oil’s role has been particularly important, with much of the world’s economic progress over the past century being ascribed to readily available oil (e.g., Hall and Klitgaard, 2012). The economic well-being of society is closely aligned with its energy supply (e.g., Tverberg, 2011), as shown in Figure 1.

Particularly when oil prices are high, discussion turns to how much oil resource remains on this finite planet. Such a peaking of interest occurred in the 1970s (e.g., Haun, 1975), and there has been renewed interest in the subject over the past decade of high prices. The issue of remaining resources is complex, involving not only raw material availability, but also questions of economics, technology, population, and ecology, to name but some areas of interaction. Political policy decisions are inevi- tably made and as scientists we can only strive to make our inputs into such discussions as objective as possible.

1 *The AAPG Memoirs are Memoir 14 (Halbouty, ed., 1970); Memoir 30 (Halbouty, ed., 1980); Memoir 54 (Halbouty, ed., 1992); Memoir 78 (Halbouty, ed., 2003); and this volume*

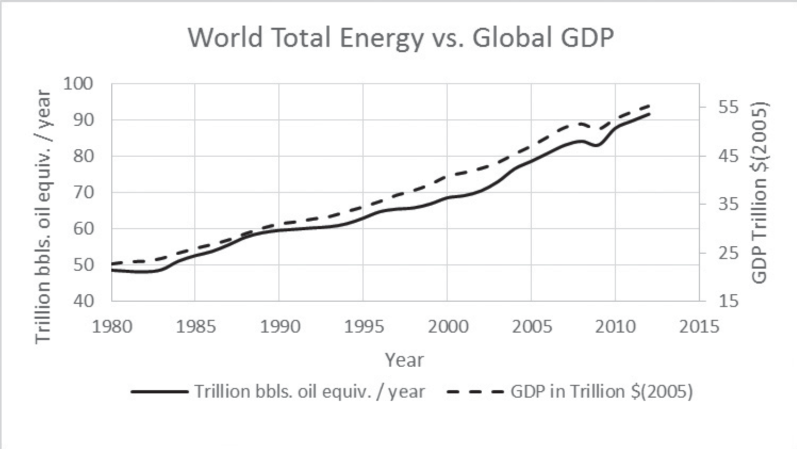

figure 1. Relationship between global GDP and world energy (sources: BP, 2014; World Bank, 2015).

The giant oil and gas fields are especially important because of their disproportionate contribution to the total oil and natural gas resource. Different approaches to using the data that the giant fields provide can result in different outlooks on the question of the remaining resource. But unless the definition of a giant field is explicit, each contribution is unique and cannot be compared with other studies. They thus fall short of the objective standard to which we aspire.

For example, Horn (2007) uses the giant field data to predict that giant fields eventually will account for only about 40% of the total amount of oil and gas re- covered, whereas Nehring (2010) argues that reserve growth from existing giants will make them a more, rather than a less, important source of oil over coming decades. Deffeyes (2001) suggests that a major increase in reserves will require discovery of at least one field larger than Ghawar. Despite the current importance of oil sand deposits and the continuous deposits such as the Bakken and Marcellus in production statistics, the objective question is whether these should be included in the statistical data for giant fields or whether they represent fundamentally different types of hydrocar- bon accumulation. Distinguishing between such dif- ferent types of deposit is common in studies of other economic resources[2]; for example, hydrothermal gold veins are clearly different from placer gold deposits.

Current giant field definition

The more recent compilation of giant fields by Horn (2003, this volume) include a definition for a giant field from Carmalt and St. John (1986): "…a giant oil or gas field is considered to be one for which the estimate of ultimately recoverable oil is 500 million bbl of oil or gas equivalent. Gas is converted to oil at a ratio of 6,000 cu ft/bbl. Some fields are, therefore, giants only because their com- bined amounts of oil- and gas-equivalent total at least 500 million bbl, and not because either resource is that great by itself." Carmalt and St. John were aware of the more precise definitions suggested by Halbouty et al. (1970) and Nehring (1978) but faced the problem that de- tailed information is not always known about reservoir characteristics. Thus it is difficult to write a precise and consistent definition to indicate when separate subsur- face pools can be combined into a single field and when they cannot. Instead, while Carmalt and St. John were precise about the giant part of the definition—equal to or greater than 500 million barrels (or oil equivalent) of ultimately recoverable oil and natural gas—they left the field part of the definition to common understanding. To paraphrase Stewart (1964), "…it is difficult to define, but I know one when I see one." And it was left at that. Statistical use of giant field data coupled with the signifi- cant technical advances that allow for exploitation of oil sands and continuous resources requires that the field part of the definition be made more precise. We suggest that compilations including both field and nonfield hy- drocarbon resources be relabeled giant accumulations to indicate that some entries are not fields and that individ- ual entries include an appropriate indication of the type of accumulation.

In Halbouty's introduction to Memoir 14, there is an explanation for using a compromise size for the giant part of the definition. Suggestions that the size be vari- able depending on access to markets, or other economic or operational details, were considered. But in the final paper of the volume, which established the public in- ventory of giants, the 500 million barrel figure was used, with a 3.5 trillion cubic feet cutoff for gas fields, which were listed separately. All subsequent compilations have used the 500 million barrel figure. However, the 3.5 trillion cubic feet of gas was changed to 3.0 trillion cubic feet (Nehring, 1978), presumably to allow a single listing of giant hydrocarbon fields. Having a single list allows for combination giants of both oil and gas.

The second part of the definition of a giant field, namely what constitutes a field, was discussed in Mem- oir 14's final paper, which contained the

2 *The analogy between types of hydrocarbon deposits and types of ore deposits was suggested by Professor Stephen Kesler of the University of Michigan (2015, personal communication)*

listing of gi- ants. The basic concept of a field was, and remains, a volume of the subsurface into which a hydrocarbon fluid has flowed. The devil is in the three-dimensional details of this subsurface volume. The original defini- tion includes phrases such as "uninterrupted by perme- ability barriers" and "separate structural closures [with] a single, or common oil/water contact" and concludes with "There are other factors which also may be used to define an area as a single field." But then exceptions were allowed for geographically close groups of small fields with the same geologic setting. These were dis- tinguished by names that included words such as com- plex, group, trend, or greater. Sometimes, the names of several smaller fields are simply combined in the list with hyphens, e.g., the Kelly-Snyder-Diamond M field. In short, an oil geologist's concept of a field was already proving difficult in definition, if not in concept.

Nehring (1978) made an attempt to make the Halbouty (1970) definition more exact. Nehring's speci- fication started with the single accumulation—noting that a single accumulation "is synonymous with a pool or reservoir"—but then narrowly expanded this defini- tion to include "a set of closely related accumulations." The expansion had to meet one of two standards: "mul- tiple pools trapped by a common geologic feature" or "laterally distinct pools within a common formation and trapped by the same type of geologic feature where the lateral separation...does not exceed one-half mile" (0.8 km). In practice, both Halbouty (1970) and Nehring (1978) tended to group accumulations of pools into a single field rather than to use their definitions to sep- arate a single field into two or more smaller fields on grounds of a precise definition. In arriving at a field def- inition, the model in people's minds was the explora- tion trilogy of source 1 reservoir 1 trap, a schema that implies fluid movement or migration in the subsurface. The overall consensus was that a field should be con- tiguous (or nearly so) on a map; that it should relate to a common source 1 reservoir 1 trap habitat; and further- more should, if possible, not be dependent on nongeo- logical factors such as political or operational criteria.

Problems With the Current definition

Following the comprehensive lists Halbouty (1970) and Nehring (1978) provided, additional compila- tions were published by St. John (1980), Carmalt and St. John (1986), and Horn (2003). The Bakken and Marcellus plays, which are discussed in this volume, do not fit the traditional concept of field and should therefore not be included in statistical compilations of field data. We are not suggesting that these important accumulations not be discussed and understood; in- deed, some argue that they represent the future of our industry. It is only that we should not include them in field statistics; they deserve their own compiled list.

The importance of what should be considered a giant field is underscored by Nehring's (2010) observation that recovery growth from already dis- covered giant fields over the coming decades will dou- ble the contribution of unconventional oil to the oil and gas resource base. In using this language, Nehring is clearly distinguishing giant fields from continuous accumulations. That this is a reasonable prediction is underscored by Klett and Schmoker (2003), who show that between 1981 and 1996, the existing giant fields accounted for an increase of 160 billion barrels of new reserves. While some of these may have been reserves reported for political reasons (Aleklett, 2012), reserve increases are also documented over this period in the United States where political factors were not an issue. An illustration of the confusion that can result from inconsistent definitions can be seen in the reserve fig- ures for Canada and Venezuela, which clearly show the addition of extra-heavy oil and bitumen-derived oil to the oil reserve statistics. The reserves themselves were not discovered in the years of increase; rather, people have known about them for decades, which makes this statistical reporting difficult to interpret. When making statistical projections, it is more useful to be able to iden- tify both reserve and production contributions from fields, especially giant fields, as opposed to the contri- butions made by other types of accumulations. At pre- sent, more and more unconventional reserves are being added to the resource base, again raising the question of whether these resources are found in oil fields.

On the other hand, the unconventional resources of Arctic areas and deep-water marine areas currently being explored will, in all likelihood, result in the discovery of fields as we intuitively think of them. To justify the high operational costs, the drilling targets almost certainly are what we geologists normally consider giant fields.

We avoid the term unconventional to describe hydrocarbon accumulations. The term's current use indicates that it has significantly different mean- ings to different people. These meanings vary, but as Berman (2015) has pointed out, they basically translate to mean "expensive." While the term unconventional may therefore contribute to economics, we don't think it contributes to geologic understanding. Furthermore, some unconventional accumulations fit the intuitive sense of a field, whereas others do not.

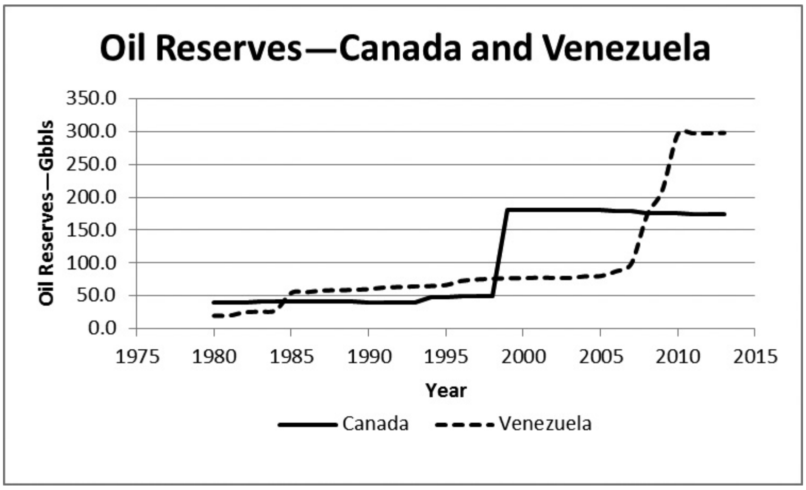

figure 2. Oil reserves of Canada and Venezuela, showing an increase based on changed definitions (source: BP Statistical Review, 2014)

A revised giant field definition

So what should the definition of giant field be? The giant part of the definition is sufficiently precise with respect to quantity: 500 million barrels of oil equivalent. Indeed, giant can refer to both fields and other types of accumu- lations. Natural gas is converted to oil equivalent at the ratio of 6000 cubic feet of gas equaling one barrel of oil. Using a single recognizably approximate conversion is preferable to a more accurate figure that might vary from field to field. But referring to the amount as ultimate re- coverable oil creates confusion with the "ultimately re- coverable resources" (McGlade, 2012) terminology used in resource evaluations; the latter contains amounts that are both as yet undiscovered or that, while discovered, are contingent on a better economic or technologic en- vironment. For fields, we believe a better description would be current estimate of final size" which can be shortened to size estimate, which is to say the sum of historic production and the 2P (proved plus probable) reserves as defined in the Petroleum Resources Man- agement System (PRMS) (SPE, 2011). In practice, this is what prior compilations seem to have used and meant. The contingent and undiscovered sections of the PRMS approach should be added to the estimated size only when the resource can be considered a 2P reserve.

Our concept of field follows the pattern established by Halbouty and Nehring in the 1970s but is made more explicit with differentiations to distinguish fields from nonfield accumulations. Our field definition thus has three components: (1) fluid composition, (2) geologic setting, and (3) geographic proximity. Accumulations that don't meet all criteria can be important parts of the hydrocarbon resource but should be distinguished as nonfield accumulations. Because the subsurface is het- erogeneous, there will be some uncertainty on the pre- cise limits in individual cases. Nevertheless, we believe that the definition will, in most cases, unambiguously distinguish a specific accumulation as either a field or a different type of hydrocarbon accumulation. An ac- cumulation that falls outside our definition but that has always been considered a single field should continue to be considered a single field. We stress that to the ex- tent possible, the definitions should rely on physical parameters and not on economic or operational criteria.

Fluid Composition

The complete gradation in nature from light oils to bitumen needs an arbitrary dividing line to separate fields from nonfield deposits. We take 10° API as the point at which the fluid is so viscous that it should be considered a nonfield accumulation rather than a field. This is a commonly used dividing line, with higher API gravities considered heavy oil and those with lower gravity being termed extra-heavy oil (Meyer and Attanasi, 2013; McGlade, 2012; SPE, 2011). The ex- isting field compilations have frequently adopted an operational definition—if the oil is produced by tech- niques used in oil fields producing lighter API gravity, then the accumulation is a field; if not, it is not. For this reason, the exclusion of extra-heavy oil from giant field compilations is imperfect. From a statistical view- point, it is best to leave existing fields alone, but use the 10° API dividing line when considering whether to call a new giant extra-heavy oil addition a field.

Geologic Setting

The geologic setting for oil and gas accumulations is the primary focus for most petroleum geologists. The oil or gas that constitutes a hydrocarbon accumulation occurs within the pore spaces of a rock, which we call a reser- voir. But a reservoir is not always a field. To be a field, the oil or gas also must be confined in the reservoir by one or more geologic features that are different from the reservoir itself. This is the aspect of our definition that distinguishes giant accumulations such as the Bakken area and the Marcellus formation from fields. The dif- ferent geologic feature may be a structure such as an anticline, one or more faults, a stratigraphic change, or a hydrodynamic regime; the critical thing is that there is something more than only the geologic character of the reservoir rock itself that is creating the accumulation. The implication is that the oil or gas would flow out of the reservoir if not for this, or these, different geologic features. Frequently, there are several different geologic features that act in concert to create the field. The classic case is a structure such as an anticline with stratigraphy that has a very low permeability formation overlying the reservoir. Implicit in such a system is that over geo- logic time the oil or gas has flowed, which is part of the implicit understanding of a field.

Geographic Proximity

Our final requirement for a field is that it be a contigu- ous (or nearly contiguous) geographic entity. There are at least two difficulties with this part of the concept. The first is how far apart the different segments can be when they are discrete segments. For example, a number of the North Sea oil fields are composed of fault blocks that have separated the subsurface pools from each other, a situation that also characterizes many Niger delta fields. The source, reservoir formation, and trapping mecha- nism is identical from fault block to fault block, so it is entirely the separation in plan view that determines whether the pools constitute one or more fields. An op- erational factor may intrude here, as we don’t advocate having a single offshore platform producing from two separate fields simply because the map view of their separation is over some arbitrary line. Such separations can also result from differing depositional characteristics such as those found in reservoirs deposited in deltaic and fluvial environments. But the greater the geographic distance separating two pools, the more justification there needs to be for considering the accumulation as a single field. We believe that one kilometer is a reason- able distance beyond which significant justification is re- quired to consider separate pools as a single field.

A second problem with lateral separations is that of two separate accumulations that overlap in plan view. Aquino et al. (2003) suggest this for the Sihil Field in the Cantarell area; Campbell (2013) describes two ver- tically superimposed hydrocarbon systems in Saudi Arabia, with gas accumulations that are below the known oil accumulations and which are generated by different source rocks. We suggest that in these cases, the likely congruence of trapping structures leads to accumulations being considered a single field, at least intuitively. So while two giants being superimposed in plan view is not impossible, we suggest that an over- lap creates the very strong preference for considering all horizons as a single field.

Conclusion

Following these ideas, we propose that the definition for a giant field in Carmalt and St. John (1986) be mod- ified to read, "A giant oil or gas field is an accumula- tion of oil, natural gas, or a combination of these that has an estimated final recovery of 500 million barrels of oil and/or natural gas hydrocarbons of no less than 10° API gravity and that are trapped in the subsurface in a single or similar geological manner and that are a contiguous (or nearly contiguous) feature in map view, with gas being converted to oil equivalent at a ratio of 1 barrel 5 6000 cubic feet."

The inevitable rough edges to this definition are not important; rather, for resource estimations and result- ing policy decisions, what is important is recognizing the giant fields as a specific subset of giant hydrocar- bon accumulations. At present, nonfield types of giant accumulation are playing a major role in changing the oil and gas industry.

As we have already noted, unconventional Arc- tic and deep-water marine exploration programs are searching for structures that, when discovered, prob- ably will fit our definition of field. On the other hand, we do not consider as fields the accumulations of ex- tra-heavy oil or bitumen. What such accumulations should be called is open for discussion. At present, there are not so many non-field giant accumulations that it is a major issue. Our preferred terms are con- tinuous accumulation for the Bakken and the Mar- cellus types where the extraction is directly from an impermeable source rock; degraded accumulations for the oil sands; and potential resources for oil shales. At least some of these are already being exploited and are making important contributions to the economy. They are giant accumulations, just not giant fields.

We are mindful of comments by McGlade (2013) about uncertainty in resource evaluations. The new types of hydrocarbon resources presently and poten- tially being developed are certainly giant in their po- tential. But not distinguishing them from fields runs the risk of devaluing the resource projections upon which policy decisions are made.

Acknowledgments

We thank the late M. K. Horn for his work in main- taining the tabulation of giant fields over the years. We are grateful both to him and to Robert Merrill for their encouragement in preparing this paper. We also thank our many colleagues who have shared and discussed "the elephants" with us over the years.

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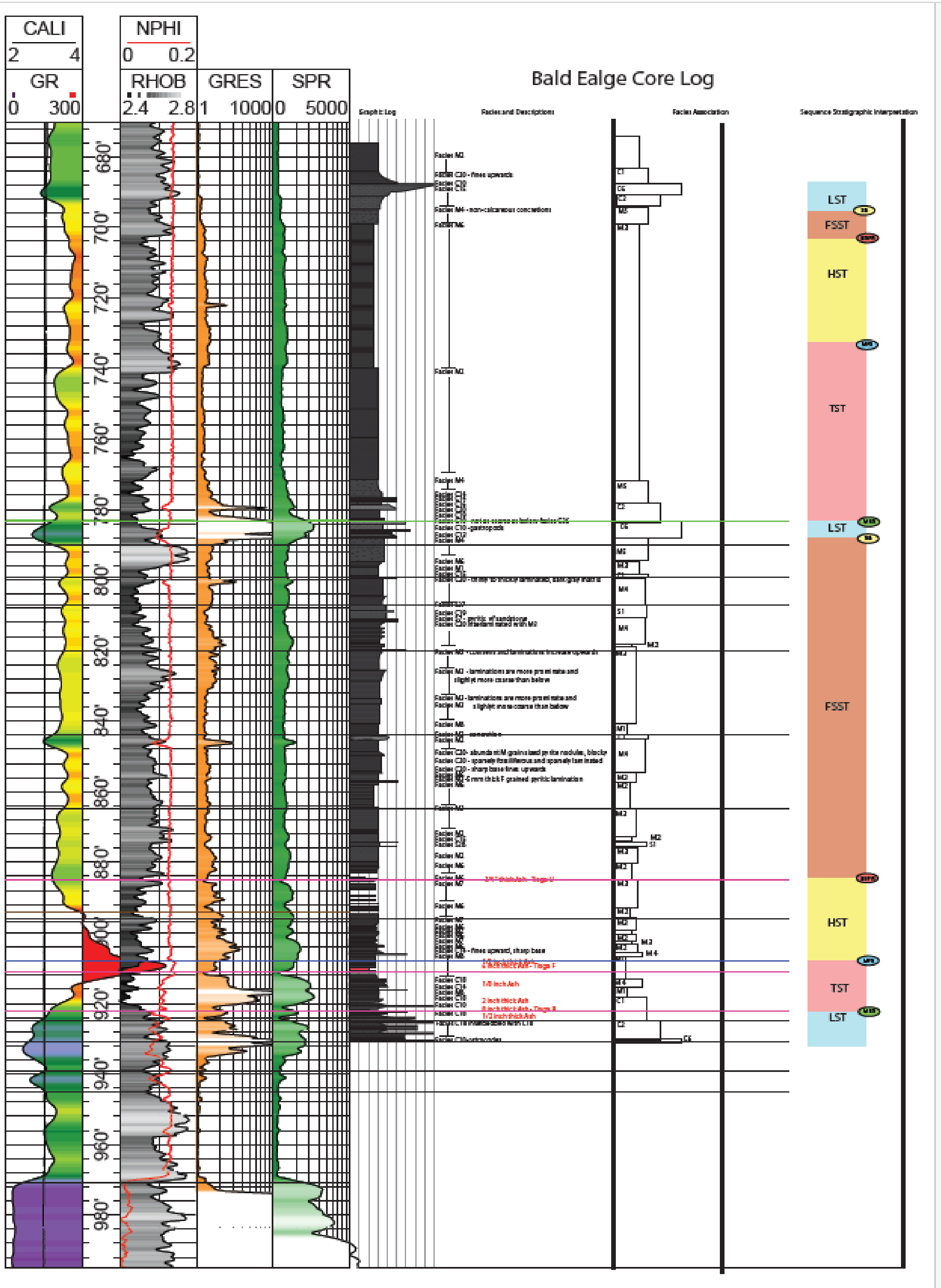
Appendix B – Bald Eagle well #1 (2009) log

Bald Eagle well, Centre County, PA, 77.656272W, 41.031778N



Appendix C - Outcrop and sample photos

Figure C-1 -- SWC-001 Roadcut at Hughesville shopping center. Photo by author at 41.224°N, 76.834°W.

Figure C-2 -- SWC-001 Roadcut near Hughesville shopping center. Photo by author at 41.224°N, 76.834°W.

Figure C-3 -- SWC-004 Anticline on I-180 near Muncy, PA. Photo by author at 41.165°N, 76.790°W.

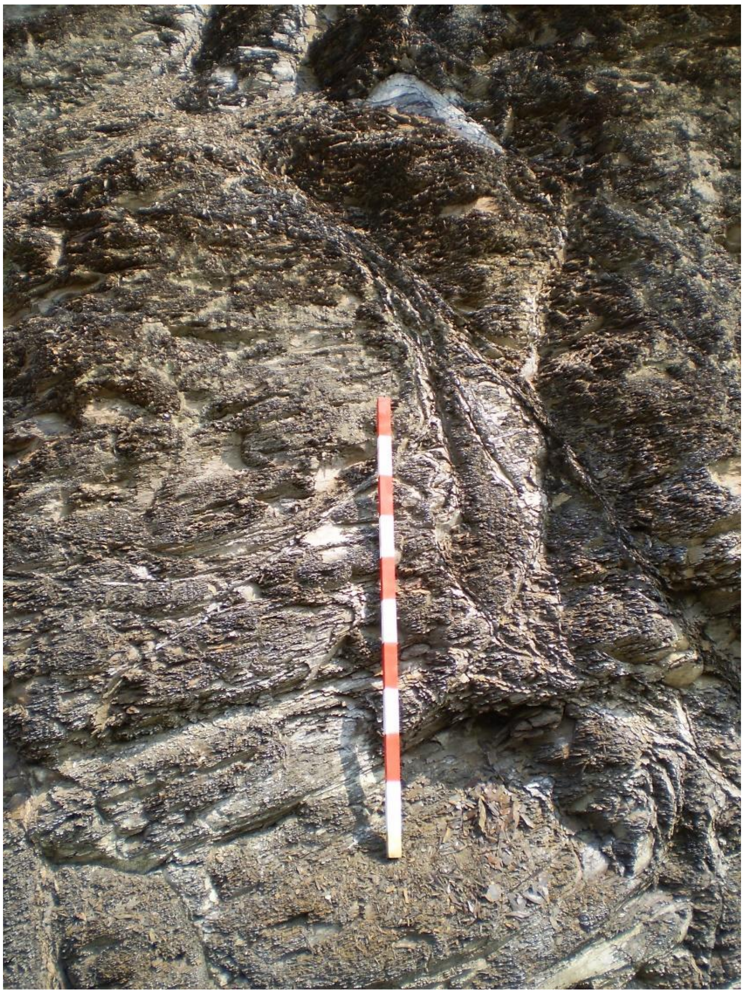


Figure C-4 -- SWC-028 Rt. 147 south of Sunbury, PA. Photo by author at 40.835°N, 76.810°W.

Figure C-5 -- SWC-029 Rt. 147 south of Sunbury, PA. Photo by author at 40.834°N, 76.810°W.

Figure C-6 -- SWC-031 Rt. 147 and Brush Valley Rd., south of Sunbury, PA. Photo by author at 40.834°N, 76.810°W.

Figure C-7 – SWC-050 Newton-Hamilton quarry. Photo by author at 40.398°N, 77.825°W.

Figure C-8 -- SWC-051 Newton Hamilton quarry. Photo by author at 40.398°N, 77.825°W.

Figure C-9 -- SWC-052 Newton-Hamilton quarry. Photo by author at 40.398°N, 77.825°W.

Figure C-10 -- SWC-053 Roadcrop near Kistler, PA. Photo by author at 40.381°N, 77.867°W.

Figure C-11 -- SWC-056 Finck quarry near Elimsport, PA. Photo by author at 41.138°N, 76.883°W.

Figure C-12 -- SWC-057 Route 54 east of Riverside, PA; near top of section. Photo by author at 40.947°N, 76.612°W.

Figure C-13 -- SWC-058 Rt. 54 east of Riverside, PA; above Tioga ash bed. Photo by author at 40.948°N, 76.612°W.

Figure C-14 -- SWC-059 Rt. 54 east of Riverside, PA; below Tioga ash bed. Photo by author at 40.948°N, 76.612°W.

Figure C-15 -- SWC-060 Rt. 54 east of Riverside, PA; basal Marcellus. Photo by author at 40.948°N, 76.613°W.

Figure C-16 -- SWC-061 Rt. 54 east of Riverside, PA; transation to underlying Onondaga. Photo by author at 40.948°N, 76.613°W

Figure C-17 -- SWC-062 Rt. 54 east of Riverside, PA; basal Marcellus. Photo by author at 40.948°N, 76.613°W.

Figure C-18 -- SWC-063 On Snydertown Road east of Sunbury, PA. Photo by author at 40.877°N, 76.702°W.

Figure C-19 -- SWC-066 Quarry on Flint Valley Road, east of Mt. Pleasant Mills, PA. Photo by author at 40.733°N, 76.986°W.

Figure C-20 -- SWC- 068 Roadcrop on Cocolamus Road, Juniata county, PA. Photo by author at 40.601°N, 77.148°W.

Figure C-21 -- SWC-070 natural outcrop on Cocolamus Road, Juniata county, PA. Photo by author at 40.606°N, 77.142°W.

Figure C-22 -- SWC-075 Small quarry on Rt. 147 south of Sunbury, PA near Hollowing Run Rd.; northern of two such small quarries. Photo by author at 40.801°N, 76.839°W.

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Figure C-23 -- SWC-077 Roadcrop on Rt. 104 at Penns Creek, PA. Photo by author at 40.866°N, 77.050°W.

Figure C-24 – SWC-092 – Roadcrop on east side of Rt. 15, south of Winfield, PA. Photo by author at 40.905°N, 76.849°W.

Figure C-25 – SWC-106 – Basal Marcellus with a Tioga ash bed, Glass Bros. quarry, Frankstown, PA. Photo by author at 40.434°N, 78.344°W.

Figure C-26 – SWC-111,112,113 – Internal decollement in the Marcellus, Newton-Hamilton quarry, PA. Photo by author at 40.398°N, 77.826°W.

Figure C-27 – SWC-140 – Basal Marcellus in core from Hamilton #1 well (at 8140 feet).

Appendix D – Book review

This review was published in the Journal of World Energy Law and Business, vol 14 (3), p.1-3.

Book review of *Up To Heaven and Down To Hell* by Colin Jerolmack (Princeton University Press, 272 pp.) [Publication date: 2021-04-20]

In 2008 the average oil price in the USA was $100 per barrel and natural gas was $8.85 per MMCF (million cubic feet). Environmentalists had been counting on “peak oil” to limit CO_2 emissions, having been unsuccessful in curbing fossil fuel production by political actions despite growing alarm about emissions and consequent global warming. For 150 years the Devonian black shales of the Appalachians have been the source for modest accumulations and production of oil and natural gas, and now “fracking” technology showed how to directly extract these resources from these impermeable shales. Penn State geology professor Terry Engelder estimated that the Marcellus shale, which is the most organic-rich black shale and underlies the Appalachians from Kentucky to New York, contained 168 TCF (trillion cubic feet) of economically recoverable natural gas by using this new technology. The rush was on.

Professor of Sociology and Environmental Studies at New York University Colin Jerolmack realized in teaching about the environment that he didn’t have sufficient information to impartially assess whether fracking was a significant environmental problem or not. With “peak oil” no longer a reason to be hopeful about CO_2 emission reductions, most environmentalists – including the majority of his students -- were using reports of pollution associated with fracking to demand a total ban on this new technology. To understand more Jerolmack spent eight months living in Williamsport, PA, where fracking (for gas, in that area) was in rapid development. He was fortunate to find a guide to the community that enabled him to meet people on all sides of the issue. This book is the result.

Many of the chapters start with a description of one or several local residents illustrating how fracking impacts their lives. We feel that we know George, Ralph, Cindy, Russ, and many others. These profiles put the environmental and social impacts on a human scale that anyone can understand; the sections read almost like a good novel. While it is clear that Jerolmack continues to be a critic of fracking, his reporting is even-handed and conveys the feelings and attitudes of those who think that fracking has had a positive impact. Furthermore, his own objections changed from specific water and air pollution to the impacts of the asymmetrical relationship between the gas companies and private landowners.

An asymmetric issue that arises immediately and throughout the book is the conflict between the owners of the land surface and the companies that own the subsurface resource (in this case gas) by virtue of either a lease or, in the case of “split estates”, by outright ownership. Obviously, the company that owns the sub-surface resource needs a way to access it. As the law has developed in Pennsylvania, and this is similar throughout the USA, the mineral owner has the right to use the surface to mine or extract the subsurface property. This allows the company not only to construct a “pad” from which to drill wells, but also to construct pipelines, install compressors, storage tanks, and other surface-processing equipment, along with monitoring devices such as remote cameras and sensors to secure all these investments. The owner of a five-acre retirement retreat, or even of a 500-acre dairy farm doesn’t have sufficiently deep pockets to challenge an oil or gas company – a lesson that most of the landowners learned only after they had leased their gas rights. While in some cases such surface disruptions may be temporary -- an impression that the gas companies want a hesitant potential lessor to have -- in other cases the disruption leaves permanent facilities and lasting scars on the landscape.

The fact that landowners signed away their rights to what, for many, was a beloved environment is the consequence of the liberal principle that the owner of land owns “up to heaven and down to hell”. Since Thomas Jefferson founded an independent United States based on the right to “life, liberty and the pursuit of happiness” – almost a direct quote from John Locke – the USA has embedded liberal philosophy in its laws and economics to a greater extent than most other nations. Even when landowners find their surface disrupted they still frequently defend their individual right, and the individual right of their neighbors, to independently make gas leasing decisions about their own property. One of the consistent themes of the book, illustrated in case after case, is the deeply entrenched belief that this liberal philosophy of equal, individual rights is fundamental to the individuals who live in the area.

The book also describes some instances of “split estates”, the parcels of land where outright ownership of the mineral rights is separate from the surface ownership. The area north and west of Williamsport has large areas of State Forest and State Game Lands which, after the

19th century logging decimated the area, have regrown into some of the largest tracts of wild lands east of the Mississippi River. Many of these lands, considered close to worthless a century ago, were purchased cheaply by the state, sometimes without the mineral rights. So when gas companies decided to exploit the area, they could sign leases with the mineral rights owner rather than the surface owner (the state). Where the state did own the mineral rights it frequently leased to the gas companies, thus removing the protection from significant areas. The state government justified its leasing decision based on forests being a 'working resource', with harvesting of timber being a regular use of such land, and viewing gas extraction as a similar, benign land use. Whoever owns the mineral rights, the oil and gas leases give the gas companies surface rights to construct pads, compressors, pipelines, access roads, and everything needed to exploit their sub-surface mineral rights. So what was supposed, in concept and in law, to be state conservation areas have, in some places, became industrial development zones. Jerolmack documents several incidences where the gas companies prohibited people from accessing these public properties, with their security guards blocking public roads, prohibiting photographs, and otherwise effectively privatizing state lands, in conflict with lease terms. In one case, the gas company tried to prevent a state forester from entering a state forest in order to do his job.

Liberal theory believes that market economics will provide for the best outcomes. But liberal economics as seen from the vantage of the owner of an inherited 5-acre remnant of land which has been in the family for generations and liberal economics as seen from the vantage of the gas company are quite different. Market economics fails in the 'tragedy of the commons'. First described by English economist W.F.Lloyd in 1833, the concept applies not only to overgrazing the common pasture, but has been the cause of many collapses. Examples include the Northwest Atlantic cod fishery in the 1990s and the mortgage-backed securities market in 2008. With respect to fracking in the Williamsport area, Jerolmack points out that the rural environment is a commons, with the birdsong, fresh air, and the calming natural rhythms of each day providing balm for both body and soul. The gas companies destroy these commons, and there is nothing the individual landowners can do about it.

This exploitation of the rural commons cannot be changed by any single landowner refusing to sign a gas lease. That owner, whether they sign a lease or not, suffers all of the same degradations of the rural environment commons as the neighbor who does sign. One of the landowners we get to know, a staunch environmentalist, signed a lease illustrating this point; justifying her decision she said ‘All the neighbors signed, so while our lease prohibits any surface access, we may as well get some benefit for the harm the companies are causing us’. In other cases landowners became so distressed that they end up selling properties held for generations, with commensurate emotional value, in order to “move off the shale”, relocating to rural areas where, they hope, the geology will not deny them the rural environment they seek.

One of the things that makes the tragedy of the commons so problematic is the asymmetry of power between the individual landowners and the gas companies. Jerolmack’s expertise, and one of the most interesting aspects of his analysis, are his observations of how the local communities have reacted. He cites instances of neighbors banding together to get better terms from the gas companies (mostly higher signature bonuses and royalty percentages), and of townships using local action to regulate siting decisions and some operating procedures (largely unsuccessfully). But local collective action has limits. When residents of one township tried to use zoning regulations to control the siting of well pads they found that state law prevented them from doing so. Throughout the narrative it becomes clear that the power of the extraction companies at the state level is significant. In Pennsylvania, industry-friendly legislation largely protects the extractive industry. At a societal level, this may explain the libertarian distrust of all government that is the typical political framework of the area.

The congressional district that includes Williamsport elects a very conservative representative to Washington and one of the book’s major contributions is to let readers better understand this. The local population is libertarian, and while they share many land use and pollution concerns with ‘environmentalists’, they have been unable to make common cause with them. The book reveals the cultural barriers to such cooperation and the resulting partisan divide despite shared concerns. The result, however, is that the power asymmetry is preserved and strengthened.

While Jerolmack was writing the book, the gas boom ended. This was due in part to the increased gas supplies initially developed and in part to the fact that production rates from fracked wells decline rapidly; both of these have caused the economics of fracking for gas in the region to become less attractive. There are still new wells being drilled, but at a much slower pace; some gas leases are being allowed to expire, undrilled. But as yet, there have been no fundamental changes to the attitudes or legal and social structures that supported the boom. As Jerolmack says in his introduction “When I moved to [Williamsport] I worried most about whether fracking tainted groundwater. By the time I left the area, my biggest concern was whether the liberty granted to citizens to lease their land, or to otherwise act in ways that limits others’ access to environmental goods, taints democracy”.

While remaining very readable, this book provides important insights into US political polarization and includes interesting excursions into US history and social commentary. And while it leads readers to ponder the relationship between politics, liberal economics, and the environment, most importantly, it provides valuable insights into the debates about global actions that might mitigate climate change to avoid a tragedy of the global commons that supports human life on earth.

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Disclaimer: While doing geological work on the Marcellus formation, I met with Ralph, who was Professor Jerolmack’s introducer and guide in the area. I have traversed much of the country about which the book is written. Throughout my life I have also spent considerable time “on the shale” in Pennsylvania, although about 100 miles removed from the Williamsport area of this book. But my neighbors are similar to the people we get to know in the book, and so for me this book was personal as well as instructive.