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Trends in Hydraulic Fracturing Distributions and Treatment Fluids, Additives, Proppants, and Water Volumes Applied to Wells Drilled in the United States from 1947 through 2010—Data Analysis and Comparison to the Literature

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U.S. Department of the Interior
U.S. Geological Survey

Cover photos. U.S. hydraulic fracturing operation (front and back covers). Photos courtesy of Mark Engle, U.S. Geological Survey.

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Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)

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Abstract

Hydraulic fracturing is presently the primary stimulation technique for oil and gas production in low-permeability, unconventional reservoirs. Comprehensive, published, and publicly available information regarding the extent, location, and character of hydraulic fracturing in the United States is scarce. This national spatial and temporal analysis of data on nearly 1 million hydraulically fractured wells and 1.8 million fracturing treatment records from 1947 through 2010 (aggregated in Data Series 868) is used to identify hydraulic fracturing trends in drilling methods and use of proppants, treatment fluids, additives, and water in the United States. These trends are compared to the literature in an effort to establish a common understanding of the differences in drilling methods, treatment fluids, and chemical additives and of how the newer technology has affected the water use volumes and areal distribution of hydraulic fracturing. Historically, Texas has had the highest number of records of hydraulic fracturing treatments and associated wells in the United States documented in the datasets described herein. Water-intensive horizontal/directional drilling has also increased from 6 percent of new hydraulically fractured wells drilled in the United States in 2000 to 42 percent of new wells drilled in 2010. Increases in horizontal drilling also coincided with the emergence of water-based “slick water” fracturing fluids. As such, the most current hydraulic fracturing materials and methods are notably different from those used in previous decades and have contributed to the development of previously inaccessible unconventional oil and gas production target areas, namely in shale and tight-sand reservoirs. Publicly available derivative datasets and locations developed from these analyses are described.

Introduction

During hydraulic fracturing, an appropriate treatment base fluid, mixed with chemical additives, and a solid-phase propping agent (proppant) is pumped under pressure into a target reservoir containing trapped oil or gas (Veatch, 1983 a, b; Ground Water Protection Council and ALL Consulting, 2009; Montgomery and Smith, 2010). The increased hydrostatic pressure results in the structural failure of the reservoir in the form of fracturing and jointing; the newly created fractures, held open by the proppant, allow oil and gas to flow more freely into the well (Veatch, 1983b). Hydraulic fracturing treatment base fluids are broadly categorized as water-based, acid-based, oil-based, or foam-based (Gulbis and Hodge, 2000; U.S. Environmental Protection Agency, 2004; Holditch, 2007), and the various treatment fluid types (treatment fluids) result from the addition of a number of different additives (Holditch, 2007). However, the exact mix of treatment base fluids, additives, and proppants is not a “one-size-fits-all” composition, but instead depends on reservoir properties, rock and hydrocarbon type, temperature, pressure, and the sensitivity of the reservoir system to water, as articulated in fracturing fluid design flowcharts (Veatch, 1983b; Economides and Nolte, 2000; Elbel and Britt, 2000; Gulbis and Hodge, 2000; U.S. Environmental Protection Agency, 2004; Holditch, 2007; Ground Water Protection Council and ALL Consulting, 2009). These variations in the use of proppants, treatment fluids, and additives result in different fracture attributes, such as fracture lengths and widths or control of fluid loss. Additionally, shale gas production has emerged largely because of the recent refinement in directional (Soeder and Kappel, 2009) and staged-horizontal drilling (Ground Water Protection Council and ALL Consulting, 2009), which can turn a vertically oriented drill bit as much as 90 degrees along a targeted strata for thousands of feet (Mooney, 2012).

Much of the recent discussion regarding hydraulic fracturing is related to shale gas production (Harper, 2008; Ground Water Protection Council and ALL Consulting, 2009; Soeder and Kappel, 2009; Kargbo and others, 2010; Gregory and others, 2011; Howarth and others, 2011; Groat and Grimshaw, 2012). In some cases, however, hydraulic fracturing is often discussed as if it has been a uniform practice, regardless of time and geologic setting, which may be due, in part, to the scarcity of publicly available and easily accessible published data and intermittent knowledge regarding the actual extent, locations, methods, and chemistry of hydraulic fracturing. As such, the controversy regarding hydraulic fracturing may have been confounded by improper comparisons between historical and current occurrences, applications, distributions, and chemistry of hydraulic fracturing and its rapid advancement over the past decades (Holditch and Ely, 1973). It has been noted that “since the advent of hydraulic fracturing, more than 1 million hydraulic fracturing treatments have been conducted, with perhaps only one documented case of direct groundwater pollution resulting from injection of hydraulic fracturing chemicals used for shale gas extraction” (Vidic and others, 2013, p. 1235009–6). It would be helpful to understand the differences between the recent applications of hydraulic fracturing to stimulate gas and oil production from low-permeability shale reservoirs and the historical hydraulic fracturing treatments in order to better qualify comparisons.

There is a need to establish a common understanding of how hydraulic fracturing drilling methods, treatment fluids, and chemical additives have changed and how the newer technology has affected the areal distribution of hydraulic fracturing in the United States. The goal of this report is to provide analyses of spatial and temporal data on hydraulic fracturing used to access natural gas from shale reservoirs, as well as on hydraulic fracturing used to access either conventional or other unconventional, continuous oil and gas resources tightly held in low-permeability and low-porosity formations (such as tight sands and coal beds) (Holditch and Ely, 1973; Veatch, 1983a; U.S. Environmental Protection Agency, 2004; Ground Water Protection Council and ALL Consulting, 2009; Montgomery and Smith, 2010). Specific objectives of this report, together with Data Series 868 (Gallegos and Varela, 2015), are to (1) identify existing data on hydraulic fracturing, (2) develop publicly available datasets of the historical and current methods of hydraulic fracturing, namely distributions, drilling methods, treatment fluids, chemical additives, proppants, and water use from the advent of hydraulic fracturing in the United States through 2010, and (3) analyze and compare the hydraulic fracturing trends aggregated from these datasets to the literature to determine the strengths and limitations of the datasets. The current debate surrounding the positive and negative effects of hydraulic fracturing will benefit from an informed and impartial understanding of this technology and the areas of oil and gas resource development that it has made accessible.

Original Data Sources and Analysis

Data Sources

The original source of the hydraulic fracturing data is the commercial IHS database of U.S. oil and gas production and well data (IHS Energy, 2011). The IHS database was selected for use in this analysis because the IHS database (1) was cited previously with respect to the number of hydraulic fracturing operations (Howarth and others, 2011), (2) was referenced as the source of water volume data from the Texas Railroad Commission (a regulatory agency for the oil and gas industry in Texas) (Nicot and Scanlon, 2012), (3) has been used by the U.S. Geological Survey previously to conduct its national oil and gas assessments (for example, Kirschbaum and others, 2002, 2003; Higley and others, 2003; Gaswirth and others, 2013), (4) has a broad temporal (1947 through 2010) and spatial (national) coverage of hydraulically fractured wells (approx.1 million) and hydraulic fracturing treatment records (approx.1.8 million) compiled since the introduction of hydraulic fracturing, and (5) has a readily usable database schema and format.

Analysis

The data from the IHS database on oil and gas production (IHS Energy, 2011), including well locations, ages, and hydraulic fracturing treatments, were used to construct derivative datasets aggregated temporally over time periods ranging from 1947 (the onset of hydraulic fracturing) through 2010 (the extent of data availability) and spatially as a function of geologic province boundaries, states, and U.S. Geological Survey (USGS) hydrologic units.[1] Descriptions of the data and details about the compilation methods are found in Data Series 868, “Data Regarding Hydraulic Fracturing Distributions and Treatment Fluids, Additives, Proppants, and Water Volumes Applied to Wells Drilled in the United States from 1947 through 2010” (Gallegos and Varela, 2015).

The data analyzed herein pertain only to the hydraulic fracturing treatments and do not include values associated with well drilling or other well completion steps. The trends based on the temporal and spatial analyses of data in the USGS Data Series 868 (Gallegos and Varela, 2015), derived from the original IHS data (IHS Energy, 2011), are compared to the literature to determine the consistencies and discrepancies of the data with the documented historical application and evolution of fracturing methodologies in the United States. Additionally, the data are used to demonstrate how the characteristics and occurrences of hydraulic fracturing have broadly changed throughout history. Because the original data contained within the IHS database (IHS Energy, 2011) are proprietary, specific measures were taken to conceal the exact

[1]The USGS unit is typically a specific stream or river watershed, or a part of a larger river’s watershed. It is defined by an 8-digit hydrologic unit code (HUC).

location of wells and prevent the release of any data directly. However, permissions were obtained from IHS to release the derivative sets of data aggregated spatially and temporally from the original IHS database (IHS Energy, 2011) and related analyses as a publicly available USGS data series (Gallegos and Varela, 2015).

Results of Data Comparison to the Literature

A number of methods have historically been used to fracture low-permeability reservoirs, including the addition of explosives (such as nitroglycerine) prior to the 1930s and later acidizing treatments to promote fracturing via etching (Montgomery and Smith, 2010). To a lesser extent, some experimental nuclear detonations have successfully stimulated gas production from tight formations (such as in the lower Piceance Basin), prompting some opponents to cite hydraulic fracturing as an alternative and more acceptable stimulation technique (Maugh, 1976; Elbel and Britt, 2000). These analyses herein, however, focus on fracturing under hydraulic pressurization ("hydraulic fracturing"), which was developed in 1947 and applied commercially in 1949 in Oklahoma and Texas (Montgomery and Smith, 2010).

Hydraulic Fracturing Locations

According to the datasets (Gallegos and Varela, 2015) derived from the original IHS database (IHS Energy, 2011), some 986,600 wells drilled in the United States between 1947 and 2010 (fig. 1) were reported to have received over 1,763,800 hydraulic fracturing treatments. Because it is possible that not all states required reporting or record keeping of hydraulic fracturing treatments, these data likely do not fully represent all hydraulic fracturing activities in the United States. Since 1947, Texas has led the Nation in the number of hydraulically fractured wells, followed by Oklahoma, Pennsylvania, Ohio, and New Mexico (fig. 2). More recently (from 2000 through 2010), the most hydraulically fractured wells were drilled (in decreasing order) in Texas, Colorado, Pennsylvania, Oklahoma, and New Mexico, whereas the largest number of hydraulic fracturing treatments were applied in Texas, Pennsylvania, Wyoming, Colorado, and West Virginia.

Figure 3 shows the more recent spatial distribution of about 278,000 hydraulically fractured wells drilled in the contiguous United States from 2000 through 2010. Table 1 and figure 4 list the geologic provinces with more than 5,000 hydraulic fracturing treatments applied to wells drilled from 2000 through 2010. These provinces include the Appalachian Basin (Coleman and others, 2011), Gulf Coast Region (Dubiel and others, 2012), Permian Basin (Schenk and others, 2008), Uinta-Piceance Basin (Kirschbaum and others, 2003), Southwestern Wyoming Basin (Kirschbaum and others, 2002), Bend Arch–Ft. Worth Basin (Pollastro and others, 2004), Anadarko Basin (Higley and others, 2011), Arkoma Basin (Houseknecht and others, 2010), San Joaquin Basin (Gautier and others, 2004), Denver Basin (Higley and others, 2003), Cherokee Platform (Charpentier, 1995), San Juan Basin (Ridgley and others, 2002), Michigan Basin (Swezey and others, 2005), Raton Basin–Sierra Grande Uplift (Higley and others, 2005), Black Warrior Basin (Milici and Hatch, 2004), and the Williston Basin (Gaswirth and others, 2013) Provinces. Along with other tight-oil and tight-gas formations (Coleman, 2009), these provinces are known to contain unconventional and (or) continuous accumulations of oil, gas, natural gas liquids, and (or) coalbed methane in low-permeability reserservoirs.

The locations of hydraulically fractured wells provided in the USGS Data Series 868 (Gallegos and Varela, 2015), derived from the IHS database (IHS Energy, 2011), are consistent with the known frontier areas for exploration and development of unconventional, continuous accumulations of oil, gas, and natural gas liquids, including tight oil and gas, coalbed methane, and shale gas, each amenable to hydraulic fracturing. Coupled with increasing costs associated with developing offshore domestic oil and gas resources, the depletion of more easily extractable oil and gas from conventional reservoirs has prompted an increased interest in the development of low-porosity and low-permeability unconventional reservoirs. Advances in hydraulic fracturing technology and the use of proppants, treatment fluids, additives, and horizontal drilling used in exploration and production operations have also contributed to the proliferation of hydraulic fracturing and the technical accessibility of oil and gas in low-permeability and low-porosity reservoirs previously considered too difficult or uneconomic to extract. The top 95 percent of these characteristics (records of treatment fluid types, additive types, proppant types, and drill-hole directions) related to the hydraulic fracturing treatments reported in the IHS database (IHS Energy, 2011) are further delineated in figure 5. These data are in the the USGS Data Series 868 (Gallegos and Varela, 2015).

Treatment Fluids, Additives, Proppants, and Drill-Hole Directions

A hydraulic fracturing fluid must have sufficient viscosity (typically 50–1,000 centipoise) to open the fracture (usually 0.5–2.5 centimeters [cm]) as well as transport and distribute proppants (normally tens to hundreds of feet from the well casing) (Veatch, 1983b; U.S. Environmental Protection Agency, 2004) under applied pressure. Additives are often applied in coordination with one another to create the treatment fluid types. The hydraulic fracturing treatments, associated drill-hole directions, proppants (fig. 5*A*), treatment fluids and fluid types (fig. 5*B*), and additive and additive types (fig. 5*C*) (Gallegos and Varela, 2015) used in three eras

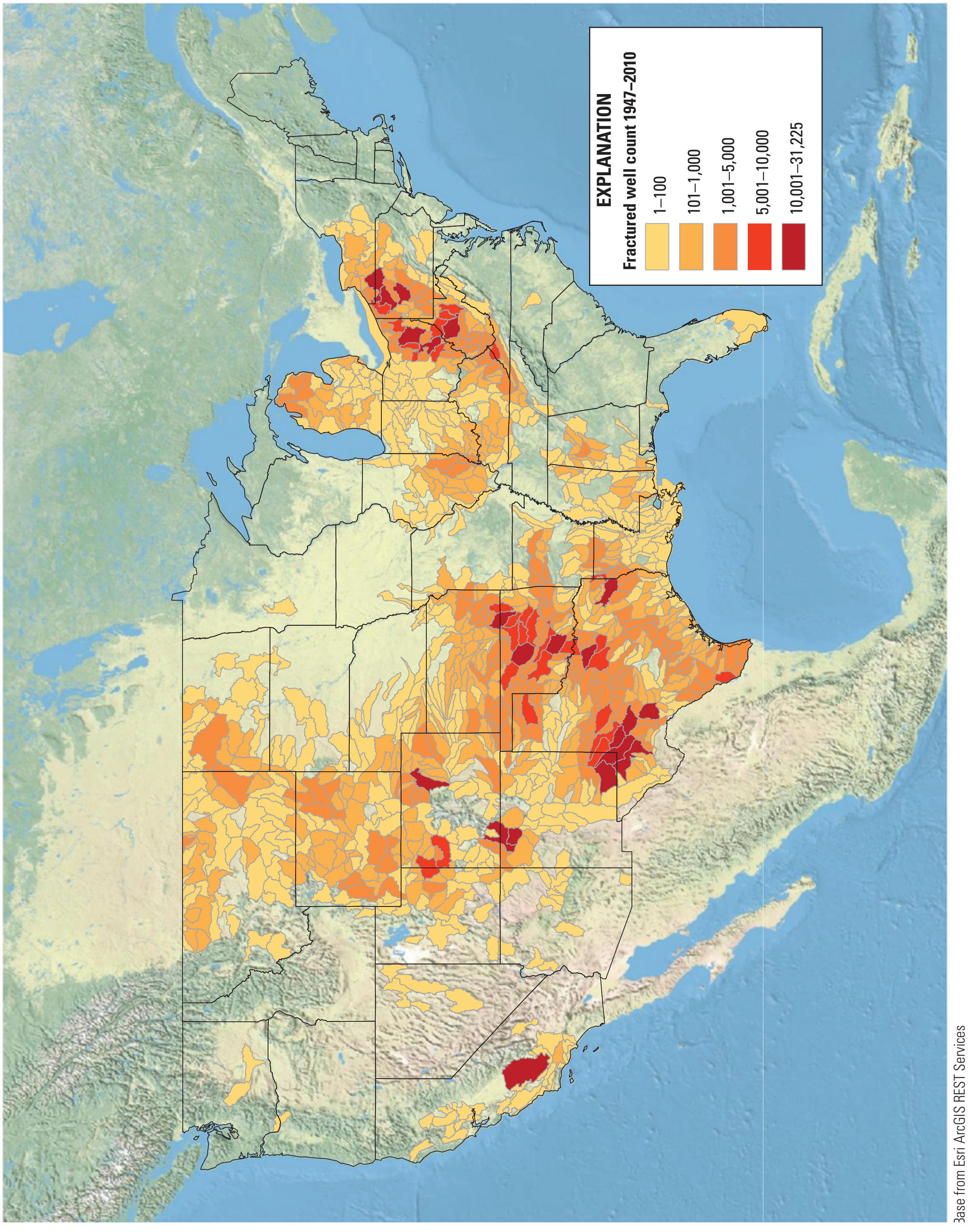


Figure 1. Distribution of nearly 986,600 hydraulically fractured wells drilled in the contiguous United States from 1947 through 2010, by U.S. Geological Survey hydrologic unit. Offshore and Alaskan wells are not shown.

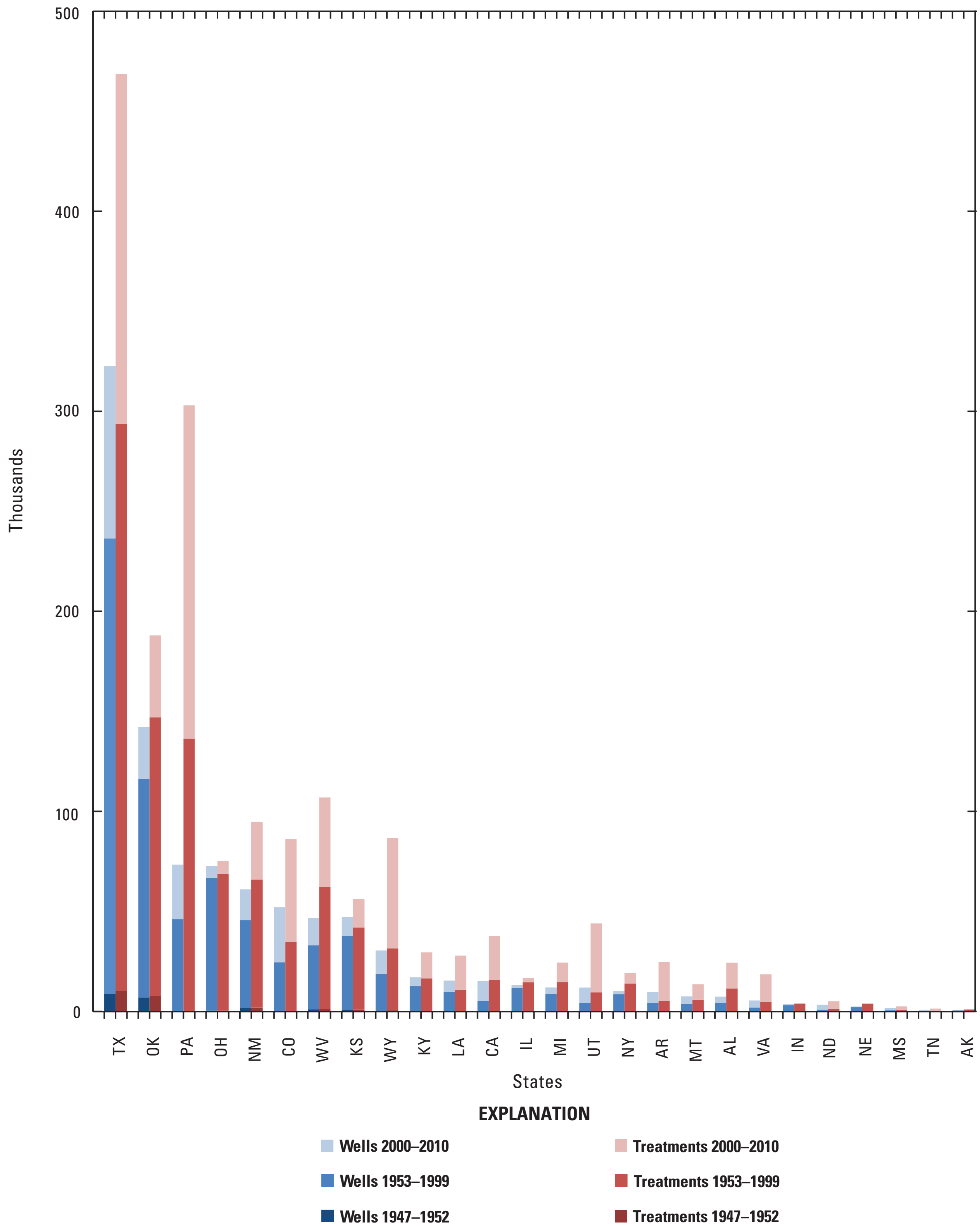
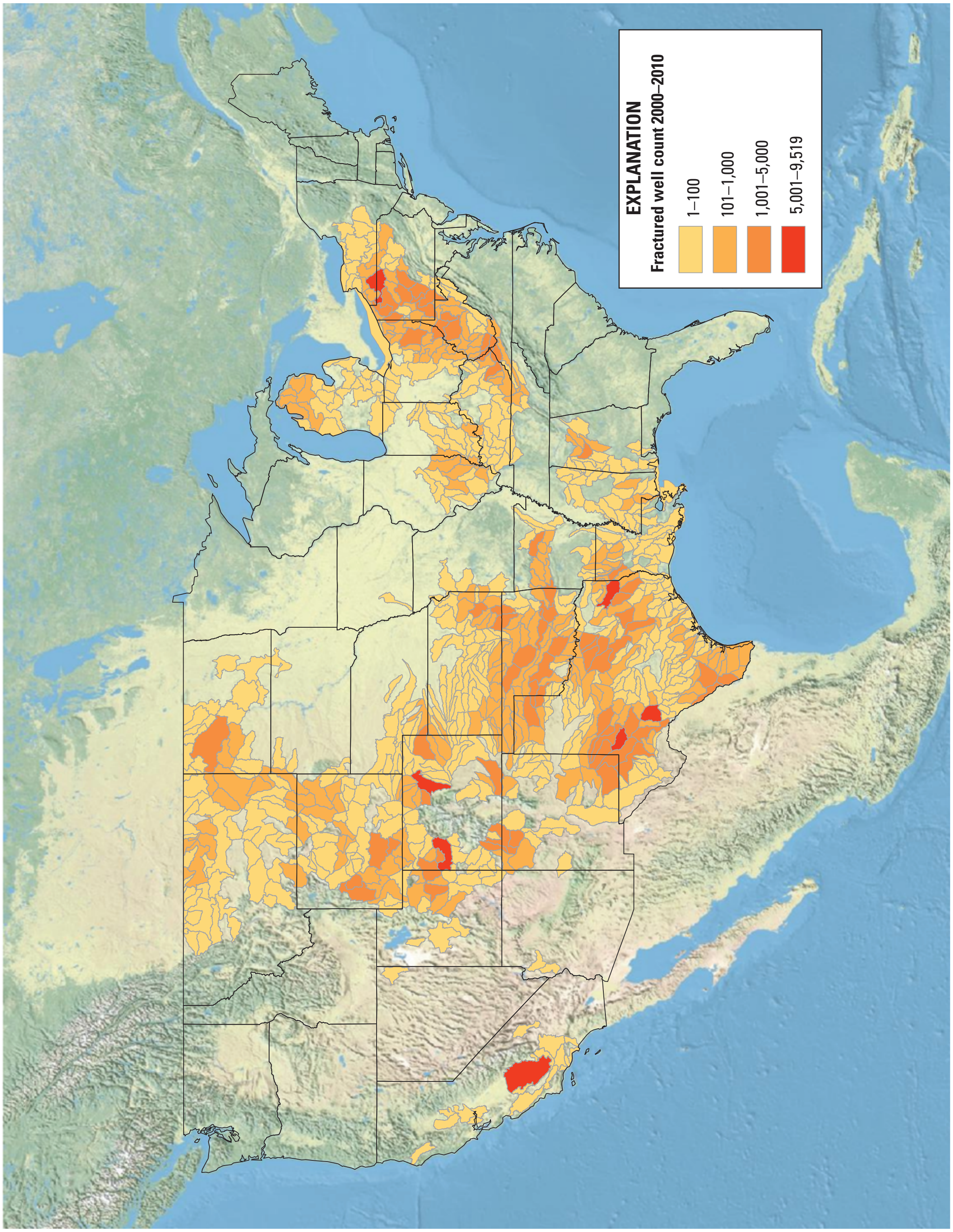


Figure 2. Hydraulically fractured wells (blue) and hydraulic fracturing treatments (red) associated with drill years 1947 through 2010 in states containing more than 50 hydraulically fractured wells and 1,000 hydraulic fracturing treatments.



Base from Esri ArcGIS REST Services

Figure 3. Distribution of about 278,00 hydraulically fractured wells drilled in the contiguous United States from 2000 through 2010, by U.S. Geological Survey hydrologic unit. Offshore and Alaskan wells are not shown.

Table 1. Geologic provinces containing more than 5,000 hydraulic fracturing treatment records associated with wells drilled from 2000 through 2010. Locations of these provinces are shown in figure 4.

Geologic province	Number of hydraulic fracturing treatment records[1]
1. Appalachian Basin	255,186
2. Gulf Coast Basins	79,069
3. Permian Basin	67,879
4. Uinta-Piceance Basin	56,182
5. Southwestern Wyoming	47,284
6. Bend Arch–Fort Worth Basin	44,683
7. Anadarko Basin	34,913
8. Arkoma Basin	28,567
9. San Joaquin Basin	21,322
10. Denver Basin	20,440
11. Cherokee Platform	16,156
12. San Juan Basin	14,802
13. Michigan Basin	9,797
14. Raton Basin–Sierra Grande Uplift	8,955
15. Black Warrior Basin	8,401
16. Williston Basin (including Bakken)	7,905

[1]Source: datasets (Gallegos and Varela, 2015) extracted from the IHS database (IHS Energy, 2011)

from 1947 through 2010 are compared below with literature citations of actual mixtures formulated for use in hydraulic fracturing to provide insight into these designations.

Years 1947–1952

The first hydraulic fracturing solutions were oil-based and included crude oil and (or) gasoline thickened with napalm (Elbel and Britt, 2000; Gulbis and Hodge, 2000; U.S. Environmental Protection Agency, 2004; Montgomery and Smith, 2010). About 92 percent of the nearly 24,400 early treatment fluids reported in the IHS database (IHS Energy, 2011) were listed as “unknown” before 1953 (fig. 5*B*). Of those treatment fluids reported (approx. 8 percent), however, a majority were described as water (32 percent), oil (30 percent), explosives (14 percent), and acid (12 percent), which is consistent with literature reports that reflect a transition during this time from fracturing using explosives or acid etching (without the use of a proppant) to hydraulic fracturing using the injection of oil-based fluids and sand to prop open the fractures, a process developed initially for stimulating sandstone formations (Elbel and Britt, 2000). Most of these treatments were applied to vertical wells to stimulate oil production (IHS Energy, 2011; Gallegos and Varela, 2015).

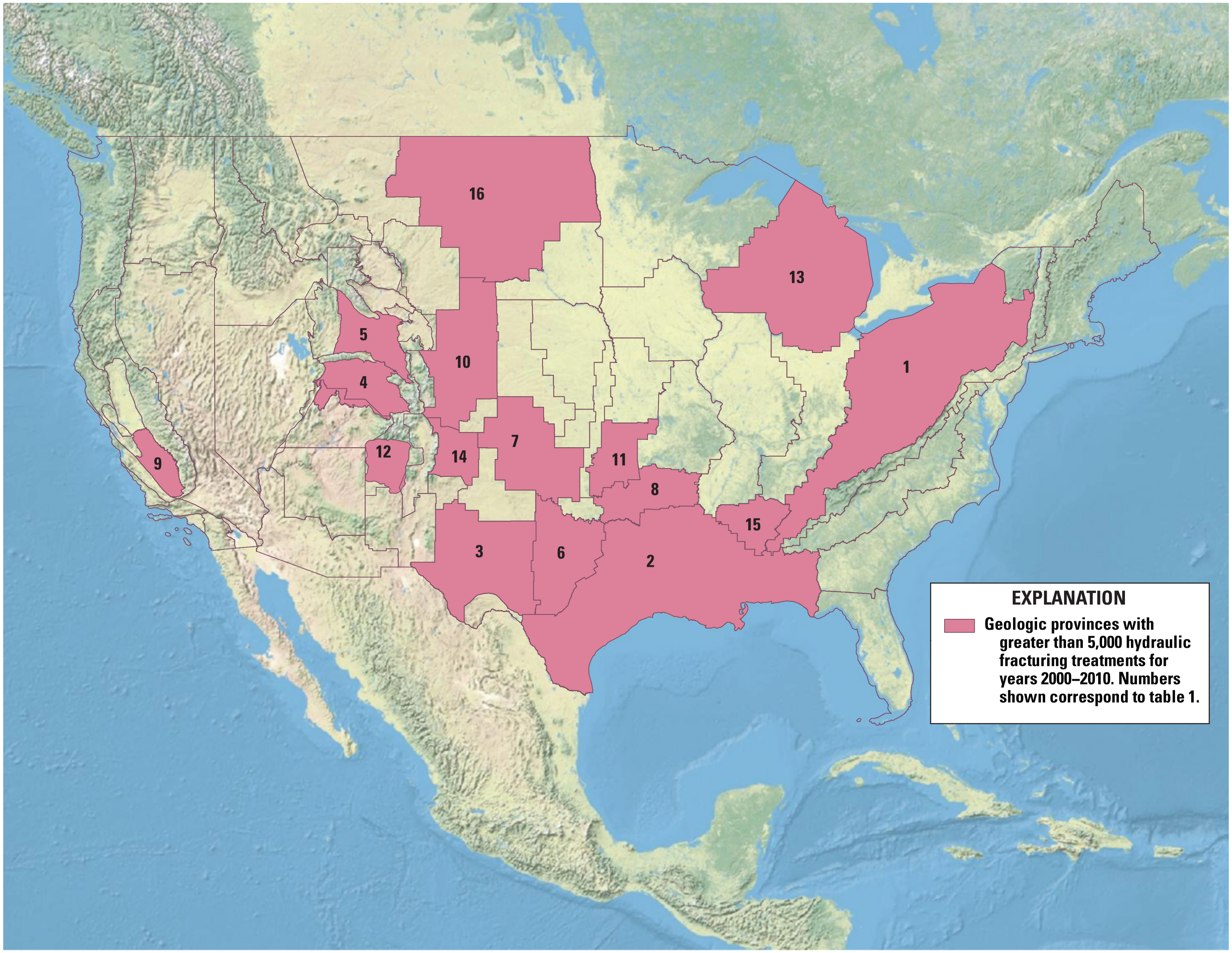
Years 1953–1999

Water was introduced as a fracturing fluid in 1953 (Montgomery and Smith, 2010), and the data show an increase in the number of records of both hydraulic fracturing (fig. 5*A*) and water-based treatments (that is, listings of “water”) at that time (fig. 5*B*) as a result. Shortly thereafter, other water-based fluids including unique service company formulations (such as My-T-Frac) also increased. The number of records of proppant use, and of sand in particular, also increased around 1953 (fig. 5*A*). Proppants are indicators of hydraulic fracturing (Elbel and Britt, 2000), and sand is often regarded as the most common proppant (Gulbis and Hodge, 2000; Montgomery and Smith, 2010). The prevalent use of sand is supported by the data (IHS Energy, 2011; Gallegos and Varela, 2015), which show that sand was used in 99 percent of reported treatments.

Less than 1 percent of the records in the datasets (IHS Energy, 2011; Gallegos and Varela, 2015) documented the use of ceramics, resin-coated ceramics, resin-coated sand, and bauxite (Gulbis and Hodge, 2000; Beckwith, 2010; Montgomery and Smith, 2010). From 1953 through 1999, nearly 992,300 hydraulic fracturing treatments were applied in large measure to vertical oil and gas wells (IHS Energy, 2011; Gallegos and Varela, 2015). The use of water-based fluids also coincides with the evolution of a number of different additives, each designed to optimize hydraulic fracturing, depending on commodity type and reservoir attributes, as described below.

Soon after the emergence of water as a hydraulic fracturing treatment fluid base, gelling agents (fig. 5*C*) such as guar gum and cellulose derivatives (Veatch, 1983b; Ely, 1985; Gulbis and Hodge, 2000), used to increase viscosity, appeared. These fluids were crosslinked with potassium pyroantimonate at low pH, borate at high pH, or aluminum to increase the effective weight of water-soluble polymers (Ely, 1985; Gulbis and Hodge, 2000), making solutions capable of suspending proppants at low temperature. Potassium chloride began to appear in the mid-1960s for clay-stabilization and to lower surface tension (Gulbis and Hodge, 2000; U.S. Environmental Protection Agency, 2004) in water-sensitive formations. Before the late 1960s, however, most hydraulic fracturing operations were small and applied to shallow reservoirs, mainly for damage removal (such as scale or paraffin deposited within the wellbore during drilling) (Ely, 1985). In the late 1970s, foam-based fracturing fluids, often generated using pressurized nitrogen (N_2) or carbon dioxide (CO_2) additives (fig. 5*B*–*C*), were also used to stimulate shallow low-pressure zones (Gulbis and Hodge, 2000) (for example, coal beds accessed for methane production; U.S. Environmental Protection Agency, 2004). Liquid CO_2 was initially introduced in the early 1960s (fig. 5*C*) for use with water- or oil-based treatment fluids and later as a sole carrier fluid to gas-lift the liquid back to the surface after treatment (Lillies and King, 1982; Veatch, 1983b).

During the 1970s, the term “massivefrac” was coined to describe hydraulic fracturing operations of deeper,



Base from Esri ArcGIS REST Services

Figure 4. Geologic provinces that contain more than 5,000 hydraulic fracturing treatment records associated with wells drilled from 2000 through 2010, listed in table 1: (1) Appalachian Basin, (2) Gulf Coast Basins, (3) Permian Basin, (4) Uinta-Piceance Basin, (5) Southwestern Wyoming, (6) Bend Arch–Fort Worth Basin, (7) Anadarko Basin, (8) Arkoma Basin, (9) San Joaquin Basin, (10) Denver Basin, (11) Cherokee Platform, (12) San Juan Basin, (13) Michigan Basin, (14) Raton Basin–Sierra Grande Uplift, (15) Black Warrior Basin, and (16) Williston Basin (including Bakken).

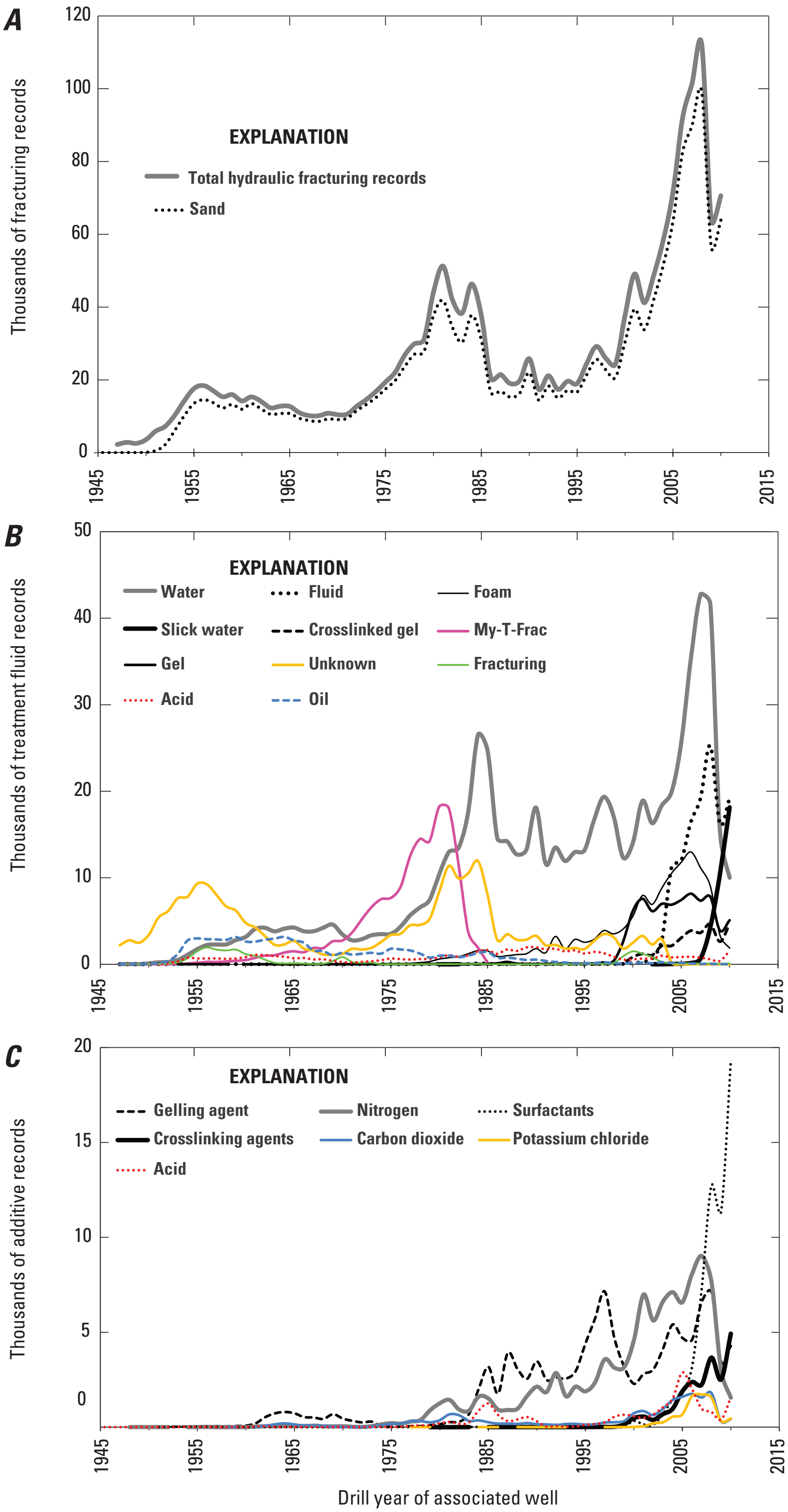


Figure 5. Total number of hydraulic fracturing treatment records associated with wells drilled from 1947 through 2010 and the top 95 percent of proppant, treatment fluid, and additive types. *A,* Hydraulic fracturing records (n = 1,763,815) and proppant records (n = 1,492,131; 99 percent are sand). *B,* Treatment fluid records (n = 1,593,683). *C,* Additive records (n = 330,501).

high-temperature formations that used nearly 1 million gallons of fluids, more than 3 million pounds of sand (Veatch, 1983a; Ely, 1985), and a more diverse mix of additives (U.S. Environmental Protection Agency, 2004) as reflected in the the data (fig. 5*C*). By the 1980s, there was better reporting of hydraulic fracturing fluids and the data indicate that water was the most common treatment fluid type (Veatch, 1983b; Gulbis and Hodge, 2000; Kargbo and others, 2010) (fig. 5*B*). Temperature-sensitive gelling agents emerged, such as hydroxyethylcellulose (HEC) polymer-based gel and a secondary gel treated with glyoxal, which activated under high temperature and low to moderate pH once it reached the formation (Ely, 1985). A similar gel-based system using hydroxypropylguar (HPG) worked well at elevated pH (Ely, 1985). These gel-bases were crosslinked with zirconium(IV) and titanium(IV) to create crosslinked guar fluids (Gulbis and Hodge, 2000), which have better temperature stability than borate (Ely, 1985). During this era, according to the IHS database (IHS Energy, 2011), 20/40 sand (425–850 microns) was used in 69 percent of hydraulic fracturing treatments and, as cited in the literature, was the dominant particle size throughout the 1990s and early 2000s (Beckwith, 2010).

Years 2000–2010

The years between 2000 and 2010 gave rise to notable changes in hydraulic fracturing treatment fluids and additives in nearly 749,000 treatments reported in the IHS database (IHS Energy, 2011; Gallegos and Varela, 2015) (fig. 5). Between 2007 and 2009, significant shale gas production began in states outside of Texas (Howarth and others, 2011), as reflected by the spike in the number of hydraulic fracturing treatments in figure 5*A*. This increase in hydraulic fracturing treatments around 2008 is also consistent with the emergence of “slick water” formulations (fig. 5*B*), as well as the increase in surfactant additives (fig. 5*C*) added to water to create the slick water treatment fluid type. Slick water is a fluid type used in hydraulic fracturing and is mostly water (approx. 99 percent) with additives (namely friction reducers, surfactants, and possibly other contents such as polyacrylamide, biocides, electrolytes, and scale inhibitors), in variable quantities, that increase fluid-flow velocity and sand transport through the borehole casing and delivery into the formation at depth (Arthur and others, 2008). Slick-water hydraulic fracturing was reported in the literature as a specialized technique for shale gas production (Rushing and Sullivan, 2007; Arthur and others, 2008; Harper, 2008; Soeder and Kappel, 2009) developed within the Barnett Shale in the 1990s (Harper, 2008). During this period, increased reporting of acid additives (fig. 5*C*), such as hydrochloric acid, indicates they were used during initial hydraulic fracturing sequences either to restore permeability lost as a result of the drilling process or to initiate fracturing (Arthur and others, 2008). Other additives commonly cited in the literature include the following:

- biocides such as glutaraldehyde (Gulbis and Hodge, 2000; U.S. Environmental Protection Agency, 2004; Arthur and others, 2008; King, 2012), ozone, chlorine dioxide, ultraviolet light (King, 2012), chlorophenates, quaternary amines, and isothiazoline (Gulbis and Hodge, 2000);
- breakers including sodium chloride (Arthur and others, 2008), oxidizers (such as ammonium, potassium, and sodium salts of peroxydisulfate), and (or) enzymes (such as hemicellulase) (Gulbis and Hodge, 2000);
- corrosion inhibitors such as N,n-dimethyl formamide (Arthur and others, 2008);
- friction reducers such as petroleum distillate (Arthur and others, 2008) or polyacrylamide (Gulbis and Hodge, 2000; King, 2012);
- iron control such as 2-hydroxy-1,2,3-propanetricaboxylic acid (Arthur and others, 2008), citric acid, and acetic acid (U.S. Environmental Protection Agency, 2004);
- oxygen scavengers such as ammonium bisulfite (Arthur and others, 2008); and
- scale inhibitors such as ethylene glycol (Arthur and others, 2008), phosphonate and polymers (King, 2012).

Finer proppant sizes reported in the IHS database (IHS Energy, 2011) as 30/50 and 40/70 also emerged in conjunction with slick water fracturing of unconventional oil and gas reservoirs (Beckwith, 2010). The rise in slick water fluids also coincided with more than 58,000 directional and horizontal wells drilled between 2000 and 2010 (Gallegos and Varela, 2015). Although most wells were vertically drilled, the proportion of newly drilled horizontal/directional wells rose from 6 percent of hydraulically fractured wells drilled in 2000 to 42 percent in 2010. About 73 percent of horizontal well treatments during this period were used to produce natural gas with the remainder used to produce oil resources (Gallegos and Varela, 2015).

Water-Based Fluid Volume Use

Several designations in figure 5*B* (“fluid,” “fracturing,” “foam,” “water,” “slick water,” and the other six fluid types plotted in the figure) have been used to describe hydraulic fracturing treatment fluids in the datasets (IHS Energy, 2011; Gallegos and Varela, 2015). Without any formal description, neither the specific chemical composition or exact water volumes can be ascertained, as many fluids vary in viscosity and density. The “water,” “slick water,” “acid,” “fracturing,” “fluid,” “sand gel frac,” “My-T-Frac,” “sand acid frac,” “gel,” and “crosslink gel” treatment fluid types, however, can reasonably be assumed to be composed primarily of water. Volumes of these water-based fluid types were summed to determine the amount of water used in hydraulic fracturing per well (Gallegos and Varela, 2015). Statistics of these water-based treatment fluid volumes are compared below to volumes cited in the literature to determine how well they represent actual reported water use during hydraulic fracturing. Table 2 shows the statistics of these water volume data (aggregated datasets [Gallegos and Varela, 2015] derived from the original IHS database [IHS Energy, 2011]).

According to table 2, a median water volume of no more than 11 cubic meters (m^3) (averages of 21 and 35 m^3) was used to hydraulically fracture vertical oil and gas wells drilled prior to 1953. This amount is substantially less than the median volume of about 311 m^3 of water used to hydraulically fracture vertical wells drilled from 2000 through 2010, which falls close to the ranges cited in the literature for typical sandstone fracturing operations (19–189 m^3) (Harper, 2008). The average volumes of 734 m^3 and 758 m^3 of water used to hydraulically fracture vertical oil and gas wells, respectively, drilled between 2000 and 2010 are slightly lower than the ranges cited in the literature for slick water–based treatments of 1,892–3,785 m^3 (Harper, 2008) per vertical well.

The median (11,007 m^3) and average (11,392 m^3) volumes of water used to hydraulically fracture horizontal gas wells drilled between 2000 and 2010 (table 2) both fall within the ranges cited in the literature—greater than 11,356 m^3 (Harper, 2008), 7,700–38,000 m^3 (Kargbo and others, 2010), 7,000–18,000 m^3 (Gregory and others, 2011), 1,900–20,700 m^3 (Nicot and Scanlon, 2012), and 6,800–33,400 m^3 (Clark and others, 2014)—but they are slightly lower than the 14,385–22,712 m^3 slick water volumes reported per horizontal well (Groat and Grimshaw, 2012). On the other hand, the median (2,709 m^3) and average (4,527 m^3) volumes of water used to hydraulically fracture horizontal oil wells fall below or on the lower end of these ranges and, in general, are lower than volumes used to hydraulically fracture gas wells. It is interesting to note that the median values of water volumes listed in table 2 are less than the average values, suggesting that the maximum reported fluid volumes skew the averages toward higher values. Both average and median water volume values, however, generally fall within ranges of water use cited in the literature. In any case, these values should be scrutinized further as more information on water volumes used in hydraulic fracturing becomes available.

In general, values in table 2 reflect (1) the generally good agreement between hydraulic fracturing water volumes

Table 2. Statistics of data on water-based fluid volumes used to hydraulically fracture oil and gas wells drilled from 1947 through 2010.

[Statistics were analyzed for the 1st–99th percentile of volumes derived (Gallegos and Varela, 2015) from well records in the IHS database (IHS Energy, 2011) that provided a drill-hole direction of "horizontal," "vertical," or "directional;" number of treatments; final status of "oil" or "gas;" treatment fluid types of "water," "slick water," "acid," "fracturing," "fluid," "sand gel frac," "My-T-Frac," "sand acid frac," "gel," and "crosslink gel;" a treatment fluid volume; and volume units. Statistics may not represent all water-based fluids applied to a single well. Volumes are for hydraulically fracturing only. m^3, cubic meters]

Hole direction	Final status	Number of wells analyzed	Hydraulic fracturing water volume[1] (m^3/well)			
			Average	Median	Minimum	Maximum
			1947–1952			
Vertical	Gas	61	35	8	0.008	375
Vertical	Oil	432	21	11	0.004	257
			1953–1999			
Vertical	Gas	148,750	292	191	2	2,960
Vertical	Oil	208,644	226	109	2	2,960
Directional	Gas	1,739	654	446	4	4,407
Directional	Oil	1,065	387	189	4	4,242
Horizontal	Gas	156	958	614	8	5,310
Horizontal	Oil	361	1,967	814	7	7,551
			2000–2010			
Vertical	Gas	88,488	758	310	2	6,635
Vertical	Oil	40,198	734	312	2	6,628
Directional	Gas	15,742	2,464	1,875	16	13,319
Directional	Oil	1,745	830	380	19	12,893
Horizontal	Gas	17,265	11,392	11,007	20	41,372
Horizontal	Oil	4,556	4,527	2,709	21	39,566

[1]Volumes originally reported in BBL, barrels; CF, cubic feet; GAL, gallons; LB, pounds; MCF, thousands of cubic feet; QT, quarts; and TON, tons. Volumes reported in nonstandard units of measure (such as "HOLE," "FT," and "SACK") were eliminated from dataset.

presented in the USGS dataset (Gallegos and Varela, 2015), derived from the original IHS database (IHS Energy, 2011), and reported in the literature; (2) substantial increases in water volumes used to hydraulically fracture wells over time; (3) the tendency for the volume of water used in hydraulic fracturing to vary as a function of target hydrocarbon (oil or gas) and drill-hole (borehole) direction of well (horizontal, vertical, or directional); (4) the ability of both median and average measurements of water volumes to represent trends in hydraulic fracturing water use; and (5) the need for more information on water volumes used in hydraulic fracturing to reevaluate data outliers.

Derivative Data Output and Recommendations

These national-scale spatial and temporal analyses of aggregated data (Gallegos and Varela, 2015) derived from the IHS database (IHS Energy, 2011) are consistent with hydraulic fracturing trends in characteristics reported in the literature, including treatment fluid types, additive types, proppant types, water use volumes, drill-hole directions, and occurrences in the United States. For example:

- The use of nitrogen and carbon dioxide additives coincided with the use of foam treatment fluid types, as expected, because these gases have been cited in the creation of foam-based fracturing fluids.
- The use of proppants, which are indicators of hydraulic fracturing, coincided with the increase in hydraulic fracturing treatments and the onset of water as a treatment fluid.
- Median and average volumes of water used in hydraulic fracturing of oil and gas wells are consistent with the ranges cited in the literature.
- The historical date of the onset of water-based hydraulic fracturing (around 1953) coincides with the rise in the reporting of “water” as a treatment fluid type.
- The total number of hydraulically fractured wells (about 1 million) compares favorably with that cited in the literature (Howarth and others, 2011; Vidic and others, 2013).
- Locations of hydraulically fractured wells compares favorably with areas of unconventional, continuous, low-permeability oil and gas resource plays.

Based on these analyses, the datasets (Gallegos and Varela, 2015) derived from the original IHS database (IHS Energy, 2011) should be used with careful consideration of their strengths and limitations, as with any other database.

- This dataset includes one of the most comprehensive sets of data describing hydraulic fracturing from 1947 through 2010 that is publicly available in a database format.
- Individual data records within the IHS database (IHS Energy, 2011) were not independently substantiated or evaluated on a small scale (such as on a well-by-well or individual treatment basis). As outlined in this analysis, however, broad trends based on the derived datasets (Gallegos and Varela, 2015) were compared to, and have been found to be consistent with, published references. As such, these derived datasets are considered sufficiently accurate to compute statistics aggregated over time and (or) geographic areas to provide an indication of tendencies of hydraulic fracturing treatments and hydraulically fractured wells within geographically and geologically defined areas (states, geologic provinces, HUCs) and over a defined period of years (1947 through 2010).
- A number of ill-defined or nebulous treatment fluid names reported in the IHS database (IHS Energy, 2011) do not have any formal description, definition, or specific chemical or water volume composition and therefore were not used to determine water volumes applied to wells. Fluid types described as “water,” “slick water,” “acid,” “fracturing,” “fluid,” “sand gel frac,” “My-T-Frac,” “sand acid frac,” “gel,” and “crosslink gel” treatment fluid types, however, were assumed to be composed primarily of water, and their volumes were consistent with water volumes reported in the literature.
- The non-normal distribution of fluid volume data, coupled with average and median values falling within or close to ranges of water use cited in the literature, warrants further scrutiny of these water volume data as more information regarding water volumes becomes available.
- Finally, because it is possible that not all states require or have required reporting or record keeping of hydraulic fracturing treatments, these data likely do not include all hydraulic fracturing activities in the United States.

Summary

These analyses have demonstrated that hydraulic fracturing treatments are neither temporally nor spatially equivalent; therefore, comparisons and assumptions regarding attributes of individual applications should be made with caution. There have been significant advancements in both drilling and treatment fluids since their initial applications, most strikingly since 2000. The most recent hydraulic fracturing production methods have resulted in a dramatic increase in oil and gas development, particularly in shale reservoir rocks previously considered too impermeable or uneconomic for exploitation. Between 2000 and 2010, the greatest number of hydraulic fracturing treatments were applied to wells drilled within the Appalachian, Gulf Coast, and Permian Basins, but hydraulic fracturing is in widespread use for the development of unconventional, continuous oil, natural gas, and natural gas liquid accumulations in most of the major oil and gas basins within the United States. Development of these resources, made newly accessible by directional/horizontal drilling and hydraulic fracturing technologies, are contributing to energy reserves in the United States. Although hydraulic fracturing is still primarily applied in vertically drilled wells, the use of horizontal drilling has rapidly emerged and is requiring an increased use of water resources.

Disclaimer

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