Lite Geology

New Oil and Gas Technologies

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Horizontal drilling and advanced hydraulic fracturing techniques have opened up new underground reservoirs for oil and natural gas development that have increased production in New Mexico and across the country. Amid environmental concerns, the trend is gaining strength. *Illustration by Leo Gabaldon.*

In This Issue...

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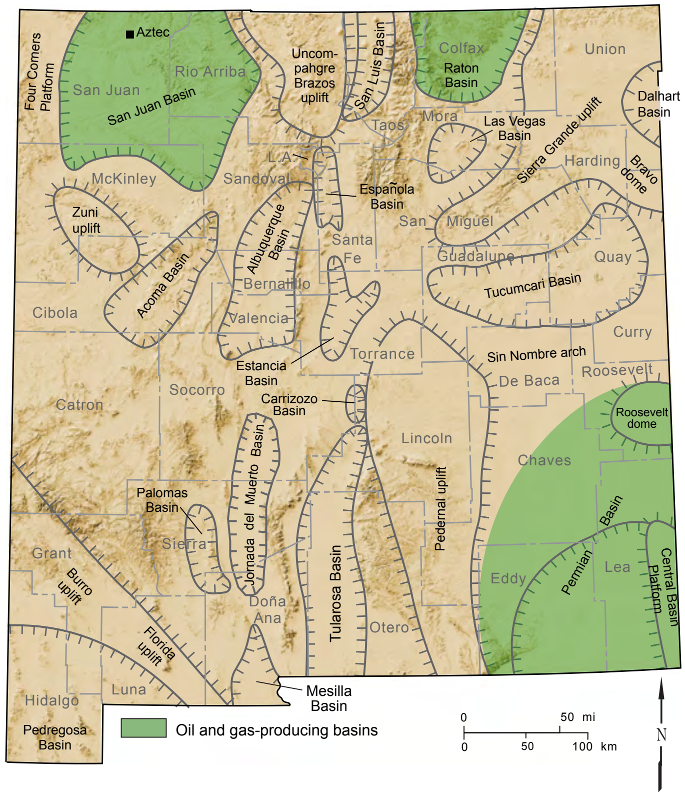
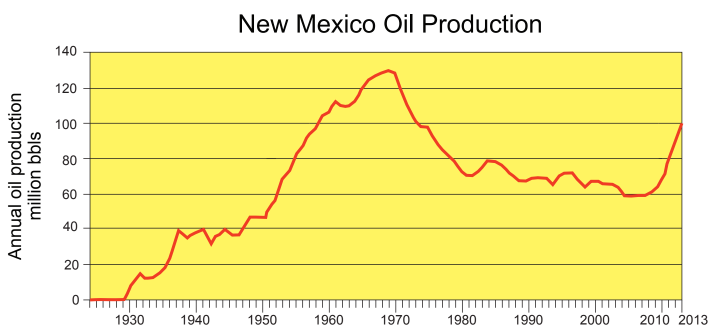
***Editor's Note:** This issue of Lite Geology is the first in a series of three issues, all related to new technologies in the energy industry. This issue will focus on the oil and gas industry, the next will be on coal, and the third will address the renewable energy sector.*



Major basins in New Mexico with oil and natural gas producing basins shown in green.



Historical annual oil production in New Mexico, in million barrels per year, from first production in 1924 through 2013. *Data from the U.S. Bureau of Mines and New Mexico Oil Conservation Division.*

New technologies have revitalized the oil and gas industry across the country, and New Mexico is a good example. A cumulative total of 5.9 billion bbls (1 bbl = 1 barrel = 42 gallons) of oil and 71 trillion cubic feet of natural gas have been produced in New Mexico since the first commercial oil and natural gas production began in the state in the early 1920s. Oil and natural gas have been produced from three of the state's many basins: the Permian Basin in the southeast, the San Juan Basin in the northwest, and the Raton Basin in north-central New Mexico. More than 95 percent of the oil has been produced from the Permian Basin with the remaining 5 percent coming from the San Juan Basin. Approximately two-thirds of the state's gas is produced from the San Juan Basin, one-third is produced from the Permian Basin, with 2 percent coming from the Raton Basin (see article on coalbed methane later in this issue). The Permian and San Juan Basins started producing in the 1920s, but the first gas production from the New Mexico part of the Raton Basin occurred in 1999. The Colorado portion of the Raton Basin began producing in the early 1980s.

Hydraulic Fracturing

In 1950 *hydraulic fracturing* (or "*fracking*," a commonly used slang term) was introduced into New Mexico as a way to increase the flow rates of oil and gas from wells. This technique involves pumping a mixture of water and sand down the well under high pressure until the compressive strength of the rock is exceeded. At this point, fractures start to form and slowly spread out, radiating from the well bore. On large fracturing jobs where large volumes of fluid and sand are used at increasingly high pressures, fractures may radiate outward as much as 2,000 feet, but their length is much less than this in most cases. Vertically, they are bound by the geologic layer that they originate in. At great depths fractures are vertical, but at depths shallower than 2,000 feet they can be horizontal. When the pressure on the water is released, the fractures stop forming and the mixture of water and some of the sand flows back into the well bore and up to the surface where it is recovered. Most of the sand remains in the fractures where it keeps (or props) the fractures open and is known as *proppant*. Most modern hydraulic fracturing fluids consist of more than 99 percent water and sand, and less than 1 percent other components. These other components increase fracture efficiency and prevent corrosion of the steel casing that lines the wellbore.

Hydraulic fracturing of reservoirs increases their permeability, and therefore increases flow rates of oil and natural gas (this technique can also be used on water wells to increase water production). With increased flow rates, it becomes possible to produce oil and natural gas economically from reservoirs with lower permeability. Without hydraulic fracturing, these lower permeability reservoirs would only yield oil and gas at uneconomically low rates of production. Hydraulic fracturing quickly came into widespread use. Since 1950, more than 90 percent of new wells drilled in New Mexico, as in the rest of the nation, were hydraulically fractured, and oil and gas that would have otherwise remained in the reservoir were produced. As a result of aggressive exploratory drilling and the advent of hydraulic fracturing, oil production in New Mexico quickly climbed and annual peak oil production of 129 million bbls was hit in 1969.

After 1969, oil production in New Mexico entered a steep decline of 4 to 5 percent per year as most of the easy-to-find oil accumulations had been discovered. As a result, newly discovered oil could not be brought online fast enough to replace depleting reserves from existing fields. This steep decline continued until 1982, at which point annual oil production had fallen to 71 million bbls, 55 percent below the peak. The decline leveled off from 1982 until 2007 when annual production had dipped to 59 million bbls. During this period, exploration concentrated on harder-to-find oil accumulations, redevelopment of previously productive accumulations whose full potential had not been realized, and increased implementation of enhanced recovery methods such as *waterflooding* (the technique of injecting water into an oil reservoir to push out oil that remains after primary production; in favorable reservoirs waterflooding can double the oil production obtained from an oil field). Redevelopment and enhanced recovery gave “new life” to old depleted oil fields.

Before 2007, oil in New Mexico was produced from wells that were drilled vertically downward until the reservoir rock filled with oil and/or gas is encountered. Steel casing is placed in the hole and cemented in place. Multiple layers of casing in shallower parts of the well protect drinking water aquifers from contamination. The casing in the depth interval occupied by the reservoir is perforated with holes that go all the way through the casing and the cement between the casing and the surrounding rock, and finally into the reservoir rock around the well. The reservoir is now in contact with the inside of the borehole. This allows the reservoir to be hydraulically fractured by a buildup of pressure from inside the casing. Production ensues when oil and/or natural gas flows from the reservoir through the perforations in the casing, into the inside of the casing, and up to the surface.

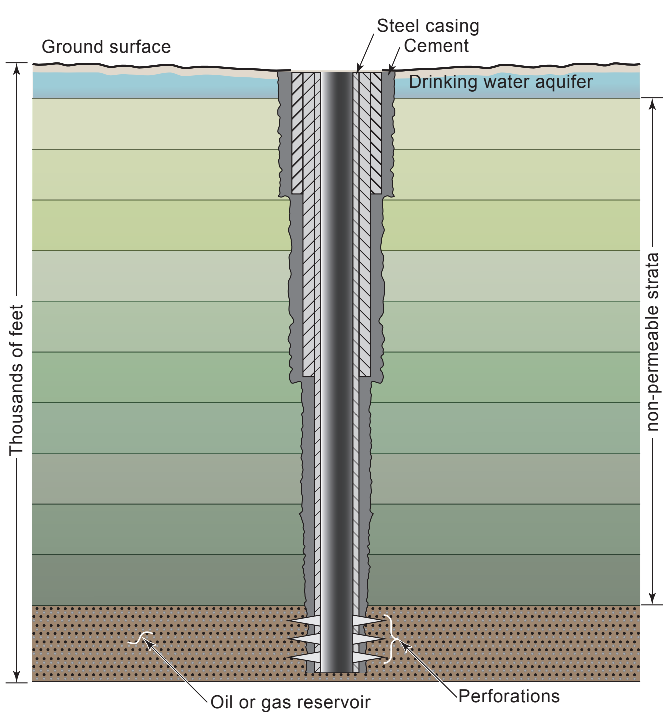
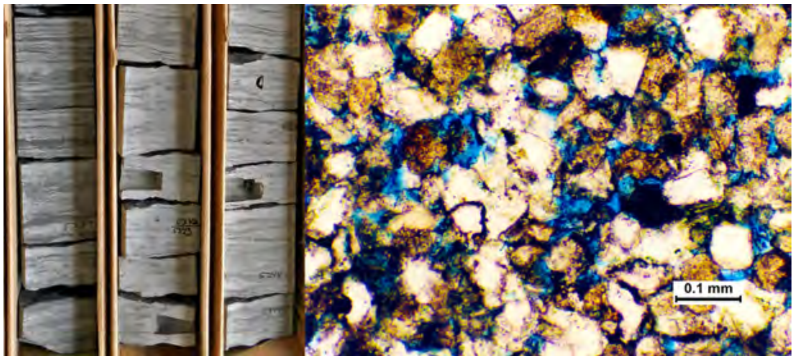


Diagram of a conventional vertical well showing steel casing, cement that bonds the casing to the rocks surrounding the well, and perforations in the casing that allow oil and natural gas to enter the well and be produced. Also shown is a shallow aquifer that supplies drinking water.

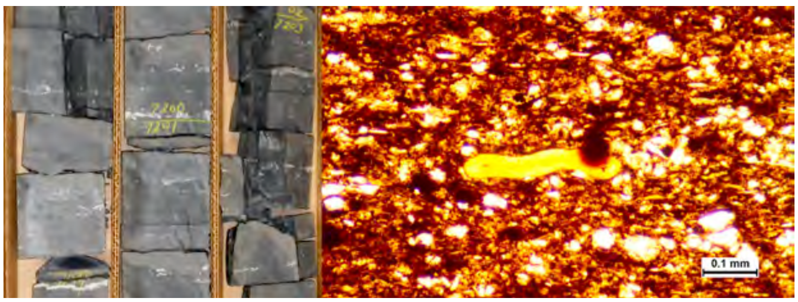
Vertical wells allow production from conventional reservoirs. In these reservoirs, the pore spaces that contain the oil or natural gas are large enough and interconnected enough to allow easy flow of fluids through the reservoir rock and into the well. In other words, the *permeability* of the reservoir rock is high. However, conventional reservoirs (mainly sandstones and certain types of limestones and dolomites) constitute only a few percent of all sedimentary rocks. The remaining sedimentary rocks, which are mostly shales, have little or no natural permeability. Some types of shales contain oil or natural gas that cannot be economically produced with conventional, vertical wells because the pore spaces in shales are very small, and will not allow fluids to flow easily through the rock.

Shale Reservoirs

Shales begin their lives as mud deposited in a variety of settings, often offshore in deep waters either in open oceans, or inland seas that once occupied large portions of the continents. In the deep, quiet offshore waters, the muds, transported mainly by rivers, settle to the sea floor. When these muds are buried by several thousand feet of overlying strata, they are converted into shales by the high pressures and temperatures associated with deep burial. This process is known as *lithification*. If the sea waters contain significant marine life, especially algae, these organisms may settle to the sea floor after death and become incorporated into the mud. With increasing burial depth and temperature, the organic remains are naturally “cooked,” and oil and natural gas form from them. This process of *oil generation* typically starts at a temperature of about 300 degrees fahrenheit, which is associated with burial depths of 10,000 to 16,000 feet (two to three miles!). It takes millions of years of “cooking” to turn the organic remains into oil and natural gas. Some of the oil and gas generated in the shale is expelled into nearby sandstones or other porous and permeable reservoir rocks, but a large portion remains in the shale.



Photograph of a core of a conventional reservoir, in this case a sandstone. The inset shows a greatly magnified view of a productive sandstone reservoir with the pore spaces shown in blue. *Photos by Ron Broadhead.*



Photograph of a core of a shale reservoir. The inset shows a greatly magnified view of shale. The dark-brown materials are organic remains that when naturally "cooked" will be partially converted to oil and natural gas. The remainder of the rock is mineral matter except for the yellow object, which is a crushed spore. In shales, the pore spaces are too small to be seen even at this very high magnification. Compare to the sandstone core above. *Photos by Ron Broadhead.*

The oil and natural gas that remain in the shales are difficult to produce because the pores within these rocks are very small, usually less than 1 micron, compared to hundreds or even thousands of microns for conventional sandstone and limestone reservoirs. These small pore sizes limit permeability and therefore flow rates. Vertical wells in shales, even if hydraulically fractured, are not capable of producing enough oil to cover the cost of drilling the well and fracturing the reservoir ($1 million or more!). Therefore, oil and natural gas resources in most shales could not be produced without losing money, and until recently these shale oil resources went almost entirely undeveloped.

Horizontal Wells and Multi-Stage Hydraulic Fracturing

In the early 2000s, however, techniques were developed to drill wells horizontally through shale. In these *horizontal wells*, the well is first drilled vertically downward to the top of the shale bed of interest. From that point, the drill hole is curved so that the trajectory of the well becomes horizontal. The remainder of the well is then drilled horizontally, typically for about 1 mile (5,280 feet), but may be as much as 2 miles. This increases the surface area of the shale reservoir that the well is in contact with compared to the contact area of a vertical well. To further increase production and to make horizontal wells economic to drill and produce, the wells need to be hydraulically fractured. Horizontal wells are much more expensive to drill and fracture than vertical wells with the total cost often exceeding $10 million! But the added oil production is often enough to offset the additional cost involved with horizontal drilling.

In most early attempts to fracture long horizontal wells, the entire horizontal length of the well was fractured all at once. This generally proved ineffective because fractures only form at the weakest points in the shale, and few fractures form. Instead, it is desirable to induce fractures evenly across the length of the well to maximize the number of fractures, and therefore maximize the surface area of the reservoir that feeds into the well, greatly increasing production rates.

M*ulti-stage hydraulic fracturing* was developed to address this problem. In multi-stage fracturing, only one short segment (or *stage*) of the well is fractured at a time. The entire length of the well may be fractured in 30 or more stages. This assures more even distribution of fractures along the length of the well, and therefore maximizes production.

Several techniques have been developed for multi-stage fracturing. They all involve isolating specific pre-determined stages of the well and fracturing each stage individually. The techniques involve either using retrievable plugs to isolate each section or they use a sliding sleeve inside steel casing inserted into the well to selectively open pre-determined intervals. Only the interval where the inside of the casing is open to the rock surrounding the well can be fractured in that stage. In this way, each segment of the well is fractured as a stage and when all stages have been completed, the artificial fractures are distributed along the entire horizontal length of the well.

Horizontal wells typically use 400,000 to 750,000 gallons of water to fracture a single well, whereas conventional vertical wells typically use less than 100,000 gallons of water per well. Where will the water used in hydraulic fracturing come from? Historically, technologies required that only fresh water, and not saline water, could be used in fracturing. This can place a strain on local drinking water supplies if enough wells are drilled and fractured during development of a shale reservoir. However, recent advances have resulted in the development of new technologies that allow the successful use of saline waters in hydraulic fracturing. Sources include re-cycled water from fracture treatments, saline water produced from deep reservoirs along with oil, and brackish waters that are too saline to be used for drinking or in agriculture. In some areas, brackish waters occur in abundant quantities. Also, liquid nitrogen (N_2, which is essentially liquefied air)

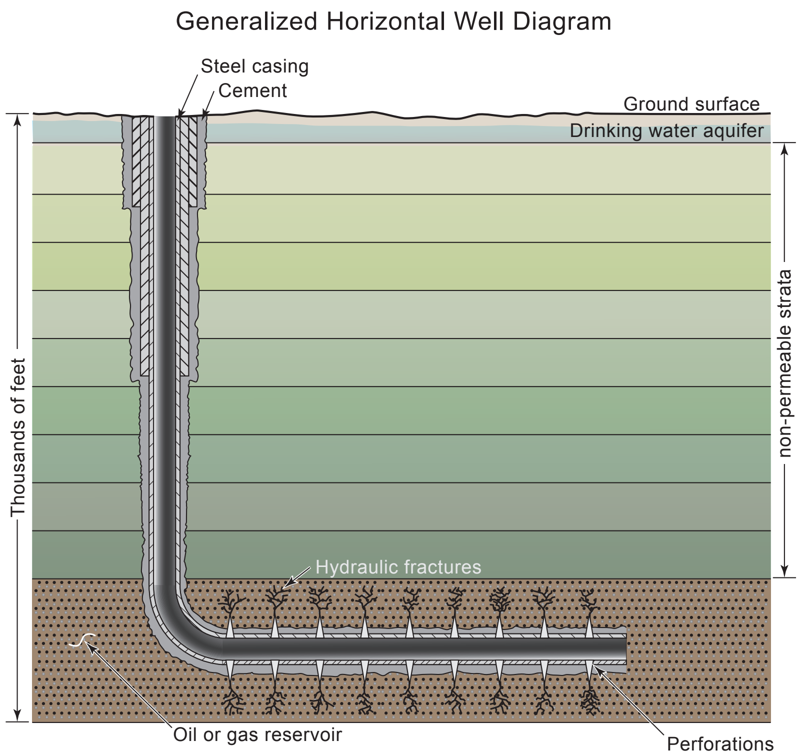


Diagram of a horizontal well, showing steel casing, cement that bonds the casing to the rocks surrounding the well, perforations in the casing that allow oil and natural gas to enter the well and be produced, and man-made hydraulic fractures that increase the permeability of the shale bed.

can be used to replace some of the water used in fracturing, another water-saving measure. And in perhaps an even greater advance, technology has recently been developed to replace water with liquid propane and butane (types of natural gas), completely doing away with the need for water in fracture treatments. This is referred to as *gas fracking*. Although gas fracking cannot be used on all reservoirs, it may be a viable option where water supplies (saline, brackish, or fresh) are scarce, and in some cases can result in better production than water-based fracturing.

The twin developments of horizontal drilling and multi-stage fracturing in horizontal wells have revolutionized the oil and natural gas exploration and production industry. This revolution has led geologists to explore for oil and natural gas in rocks of very low permeability. Shales have been the major target in several basins throughout the United States and elsewhere in the world. In New Mexico, a number of possible targets exist but horizontal drilling has thus far been applied mainly to shales in the Permian Basin. Chief among these is the Bone Spring Formation, and especially shales and lenticular sandstones within the shales which lie at depths of 10,000 to 12,000 feet (two miles!).

Since initial efforts to use horizontal drilling in southeastern New Mexico began about five years ago, the pace of drilling horizontal wells has increased significantly. During 2011 there were 1,489 oil and natural gas wells drilled in New Mexico, the majority of which were drilled horizontally. As a result, huge oil resources that previously had been unrecognized are now being produced. New Mexico has seen explosive growth in oil production over the last five years with production increasing by 2 percent in 2009, 7 percent in 2010, 9 percent in 2011, 19 percent in 2012, and 17 percent in 2013. Oil production was 99 million bbls in 2013, a level not seen since 1974. This year-to-year growth in production exceeds even what was seen in the 1950s. New Mexico is on its way to achieving a second and very substantial peak. There will be a positive effect on oil production for decades to come as horizontal drilling and multi-stage hydraulic fracturing allow oil to be produced that is economically inaccessible with conventional vertical wells.

Suggested online reading

United States Geological Survey map of assessed shale gas in the United States: **http://pubs.usgs.gov/dds/dds-069/dds-069-z/downloads/DDS-69-Z_plate1.pdf**

New Mexico oil and gas production with examples of selected shale resources: **http://geoinfo.nmt.edu/staff/broadhead/documents/BroadheadLegislaturehandoutv3.0.ppt**

The Mancos Shale in the San Juan Basin: **http://geoinfo.nmt.edu/staff/broadhead/documents/MancosShaleslideset.pdf**

The economic impact of shale oil and gas production in the United States: **http://www.searchanddiscovery.com/documents/2013/70147beaumont/ndx_beaumont.pdf**

Energy from shale website: **http://www.energyfromshale.org/hydraulic-fracturing/what-is-fracking?gclid=CJzG2N_Gl7sCFYqPfgodrhQAIg**

Hydraulic Fracturing and the Environment

Valid environmental concerns have been raised about the environmental effects of hydraulic fracturing. Chief among these concerns are two questions. First, will hydraulic fracturing result in the contamination of drinking water aquifers? And second, where will the water used in hydraulic fracturing come from? While some technological developments for water supply are addressed in this article, a detailed discussion of these complicated and controversial topics is beyond the scope of this article. However, in-depth discussions can be found in the following references:

Geological Society of America discussion of hydraulic fracturing: **http://www.geosociety.org/criticalissues/hydraulicFracturing/index.asp**

American Association of State Geologists Fact Sheet on Hydraulic Fracturing: **http://www.stategeologists.org/temp/AASG%20Hydraulic%20Fracturing%20statement.pdf**

National Ground Water Association position paper: **http://www.ngwa.org/Documents/PositionPapers/hydraulic-fracturing-position-paper.pdf**

United State Geological Survey discussion: **http://energy.usgs.gov/OilGas/UnconventionalOilGas/HydraulicFracturing.aspx**

United States Environmental Protection Agency discussion: **http://www2.epa.gov/hydraulicfracturing**

New Mexico Oil and Gas Association: **http://www.nmoga.org/hydraulic-fracturing**

Economic Benefits and the Future of Oil and Gas in New Mexico

Ron Broadhead

Oil and natural gas production and associated drilling and processing activities form the backbone of New Mexico's economy. These activities provided 29 percent of New Mexico's general fund revenues of $5.7 billion during fiscal year 2013 (7/1/2012–6/30/2013), which equals over $1.6 billion. These revenues include:

- $411 million in production taxes
- $70 million in lease bonuses and rentals from state trust lands
- $403 million as New Mexico's share of royalties obtained from federal lands
- $576 million in gross receipts and income taxes associated with industry activities
- about $180 million from the Severance Tax Permanent Fund (funded almost entirely by taxes on oil and gas production)

(Source, slideset published by Tom Clifford, New Mexico Secretary of Finance and Administration).

In addition, more than 95 percent of the money in the State Land Grant Permanent Fund is derived from royalties on oil and gas production, with annual distributions of $500 million to the fund beneficiaries (chiefly public schools, but also others such as universities and the Children's Hospital). Local governments in productive counties received $341 million in equipment and production taxes. More than 13,000 jobs in New Mexico are directly dependent on oil and natural gas production.

Most of these benefits in the future will depend on continued production. How much oil and natural gas can be produced by horizontal drilling in New Mexico? How long will the production last? At this point, there are no exact answers to these questions. Oil that can be produced with horizontal drilling is just starting to be tapped. Years, if not decades of drilling remain within the Bone Spring Formation alone. Several other shale formations in the Permian Basin remain incompletely evaluated and unproduced. In addition, exploration for oil and natural gas in the Mancos Shale in the San Juan Basin is in its infancy, but initial results of exploratory drilling are very favorable. This may well revitalize the San Juan Basin, largely a gas-productive region that has been in decline in recent years. With oil production climbing at rates not seen in 60 years, and with shales just starting to be drilled, the future of oil and gas production in New Mexico is very bright. Maximum development of this resource is decades away.

Horizontal drilling for natural gas has not yet had an impact on New Mexico. The current low prices ($3 to $4 per thousand cubic feet) of natural gas are too low to justify the drilling of large numbers of very expensive horizontal natural gas wells. Therefore, shale gas exploration has been minimal. Shales with gas potential in the Permian Basin have not yet been pursued. However, limited geologic studies and drilling indicate substantial shale gas resources await further exploratory drilling and assessment in the San Juan, Permian, Raton, Tucumcari, Las Vegas, Albuquerque, and Pedregosa Basins.

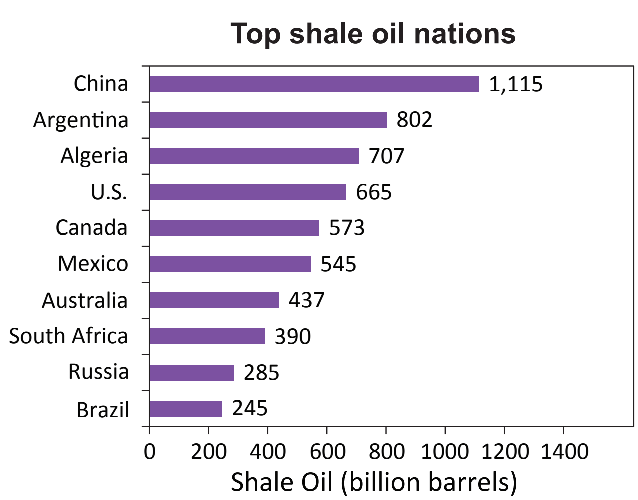
Because the technology is so new, oil and natural gas reserve and resource estimation in shales is in its infancy. What is clear is that the total volume of oil and natural gas in shale is enormous, and may well exceed the volume of oil and natural gas in all conventional reservoirs. Production and reserve characteristics of wells will vary from shale to shale and even within individual shale units. The evaluation of oil and natural gas resources in shales is a very challenging and rapidly evolving field of scientific study. Many fascinating challenges await future geologists.

Global Impacts of the Shale Oil and Gas Boom Maureen Wilks

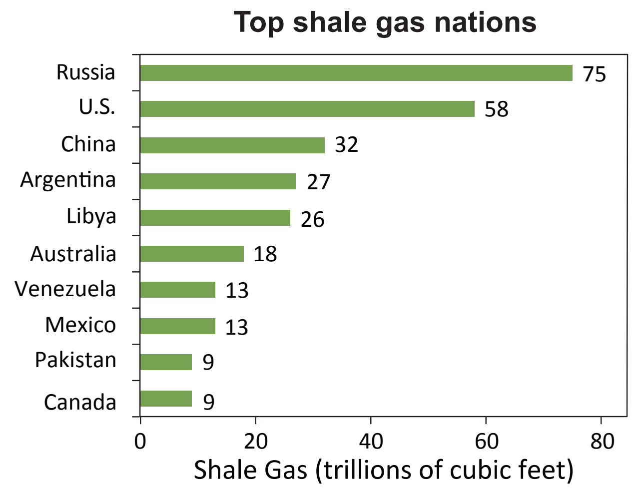
Where in the World are Shale Oil and Gas Resources?

In the last ten years, advances in drilling technology for unconventional resources have greatly changed shale into a long-term viable source of hydrocarbons in North America. For the first time in nearly two decades, the U.S. extracted more oil from the ground than it imported from abroad in October 2013, marking an important milestone for a nation seeking to wean itself off foreign oil. The U.S. has just become the world's largest producer of natural gas. Within the next two years the U.S. will overtake Russia as the world's largest oil producer, thanks to its shale oil boom, which is transforming the global energy landscape.

In addition, countries outside the U.S. and Canada have vast quantities of hydrocarbons yet to be tapped from shale formations. Ten percent of the world's recoverable oil resources and 32 percent of the world's recoverable gas resources are in shale formations. So far only the U.S. and Canada have produced shale oil and shale gas in commercial volumes. However, more than half the identified or known non-U.S. shale oil resources are in Russia, China, Argentina, Algeria, Canada, and Mexico. There has been interest expressed, or exploration activities begun, in shale formations in a number of countries including Algeria, Argentina, Australia, China, India, Mexico, Poland, Romania, Russia, Saudi Arabia, Turkey, Ukraine, and the United Kingdom. Cutting-edge technologies are also allowing new parts of the globe to tap into unconventional energy resources, including deep offshore natural gas beds. Places like Cyprus in the eastern Mediterranean, and Mozambique in Africa hold promise with energy reserves.



Data from U.S. Energy Information Administration.



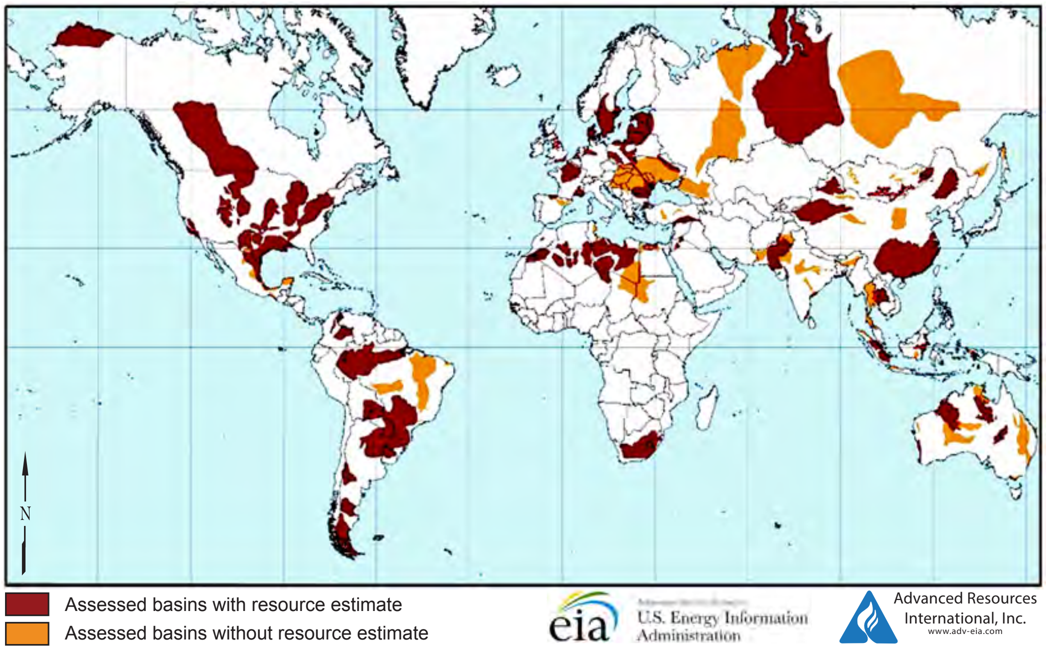
Data from U.S. Energy Information Administration.

Who is Leading the Way and Why?

The U.S. has led the way in the boom in extraction of shale oil and gas. The advent of large-scale shale gas production began around the year 2000 when shale gas production became a commercial reality in the Barnett Shale in north-central Texas. Extensive drilling in the Bakken Shale in North Dakota and the Marcellus Shale in Pennsylvania has catapulted these states from minor oil producers into two of the top producers in the nation. Many factors give the United States a head start in exploiting energy locked in shale, including its access to cutting-edge technology and risk capital, clear private resource ownership, and huge numbers of drilling rigs. The U.S. has 60 percent of the world's drilling rigs; 95 percent of them are capable of the difficult horizontal drilling required for shale production. There are also hundreds of small independent companies ready to develop new resources and technology.

However, given the variation across the world's shale formations in both geology and above-the-ground conditions, the extent to which technically recoverable shale resources will prove to be economic is still unclear. Some countries like France have flat-out banned hydraulic fracturing, which is required to develop shale resources, due to environmental concerns. Currently France derives most of its electricity from nuclear power.

Algeria, on the other hand, is eager to utilize tax breaks to encourage shale gas exploration. The country's relative stability is appealing to foreign operators and investors. Adding to the appeal, the vast stretch of near-empty desert offers the advantage of fewer drilling risks, and pipelines are already in place beneath the Mediterranean Sea to Spain and Italy. These lines link Africa's largest gas exporter to the European grid.



Map of basins with assessed shale oil and shale gas formations, as of May 2013.

Changing the Political Landscape

The U.S. resurgence as an oil producer is already changing the dynamics of international energy markets. OPEC (Organization of the Petroleum Exporting Countries), which for many decades has controlled the supply and price of oil, is seeing its global dominance challenged by the surge of supply from non-OPEC countries like the U.S., Canada, Argentina, and China.

The shale revolution is likely to perpetuate U.S. dominance, not just in geopolitics, but in the energy industry itself. Many experts predict that North America will become energy independent in the near future, for the first time in decades. As production goes up and imports go down, there is a positive macroeconomic effect for the U.S. It's good for the balance of payments, good for the dollar, good for jobs, and for other heavy industries. For the first time since the 1970s, new petrochemical plants have been built in the U.S. These newer plants use gas rather than crude oil, and it's once again economic to make petrochemical products such as plastics and synthetic fabrics in the U.S. It has also resulted in depressed natural gas prices to the consumer, so it's cheaper to heat your home. The increased use of natural gas in generating electricity has also resulted in a decline of carbon dioxide emissions in the U.S. (a greenhouse gas associated with global climate change), resulting in the lowest total emission levels in over two decades.

While many countries have massive shale reserves—China is the most notable but Algeria, Argentina, and Mexico are others—none is thought likely to be able to take advantage of their deposits quickly or easily, certainly not like the explosive growth already seen in the U.S. A potential loser in this boom is Russia, as European nations find alternate suppliers for natural gas. The Russian share of the European Union's natural gas imports is expected to drop from the current 34 percent to below 15 percent over the next 10 to 15 years, replaced by supplies of liquefied natural gas from the United States. Furthermore, major producers like Russia will have to invest billions of dollars into new pipelines to Asia as they can no longer rely on demand from the West, and will have to deal with an increasingly assertive Beijing.

A Cautionary Note

There are long-term uncertainties about the productivity of shale formations, because many are very large and only limited portions have been tested for production. In some cases, earlier gas assessments have been dramatically lowered. In 2011 Norway's shale gas assessment was 83 trillion cubic feet, but after disappointing results obtained from three Alum Shale wells drilled by Shell Oil Company in 2011, it's been dropped to zero. The Shell wells were drilled in the less geologically complex portion of the Alum Shale in Sweden, which significantly reduced the prospects for successful shale wells in the more geologically complex portion of the Alum Shale in Norway. However, rapidly advancing technology and ever-changing energy economics cause resource estimates to continually change.

Coalbed Methane—Natural Gas from Coal Douglas Bland

Most natural gas in the past has been produced from underground sandstone and limestone rock formations. Recently, advanced technologies including horizontal drilling and hydraulic fracturing have allowed shale formations to also produce substantial amounts of gas. But what about coal?

Coal has been recognized as a fuel source for centuries, but it was only mined and burned for heat. Thousands of miners have been killed in coal mines, often due to explosions caused by accumulations of methane, or natural gas, seeping out of the coal into the mine tunnels. A spark would ignite the gas, causing an explosion. But what if the gas could be produced as a fuel by itself?

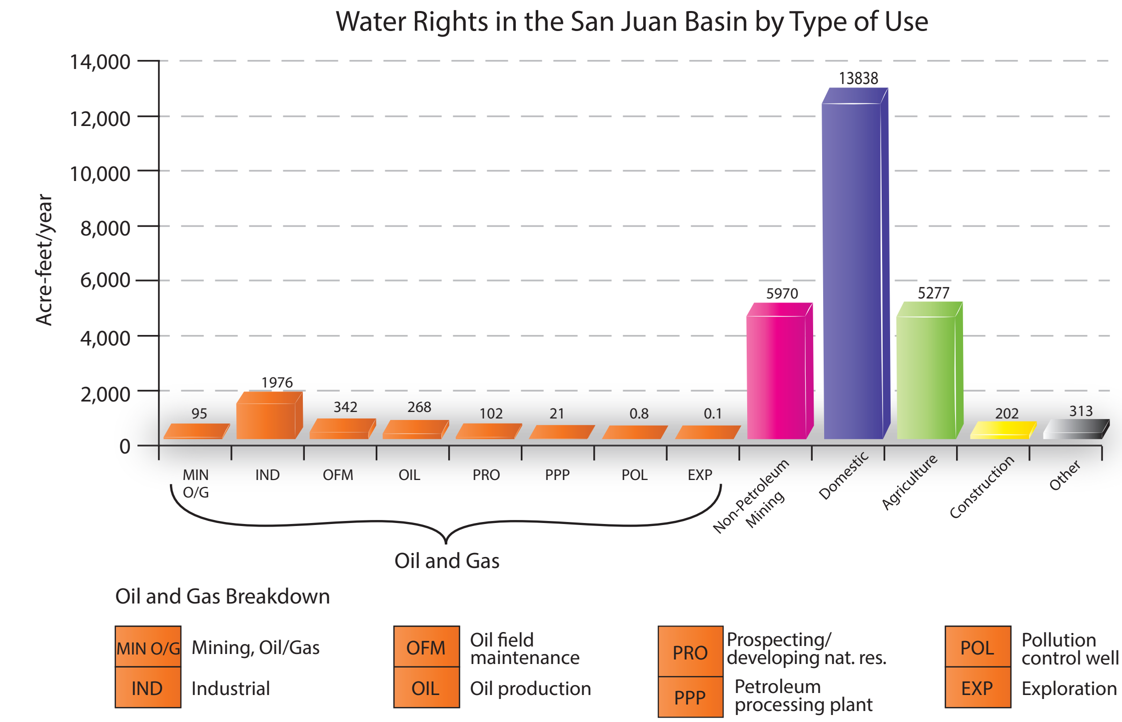
During the 1980s in the San Juan Basin of northwestern New Mexico, oil and gas companies established the first high-rate commercial coalbed methane wells in the coals of the Fruitland Formation. Initially the wells were drilled using conventional methods, including hydraulic fracturing. Later, a unique method was developed whereby the pressure on the coal around the well caused by the weight of the fluid in the wellbore was reduced by replacing the fluid with air or foam. This caused the coal on the sides of the wellbore to cave in, creating a cavity. It also created fractures farther out in the coal formation. This "cavitation" created additional pathways for gas and water to flow into the wellbore. Initially, large amounts of water were produced. As the formation pressure decreased through de-watering, natural gas adsorbed on the coal began to flow into the well. Through time, water production decreased and gas production increased. Coalbed methane as a significant new source of natural gas was born.

New Mexico was the 7th largest producer of natural gas in the nation in 2011. Starting in the 1990s, coalbed methane has supplied about one third of our state's annual gas production, often topping half a trillion cubic feet (tcf) of gas. Total production from the San Juan Basin of New Mexico and Colorado exceeds 20 tcf, and accounts for two thirds of all coalbed methane production in the U.S. to date. Until 1999, all New Mexico production came from the Fruitland Formation. That year, a pipeline was completed and coals from the Raton Basin began producing coal gas from the Vermejo and Raton Formations in northeast New Mexico, although Colorado had established production from its portion of the basin several years earlier.

Production rates in the San Juan Basin have declined somewhat in recent years, and early estimates of gigantic reserves have been downgraded. Most experts believe that even though the height of production may be over, significant reserves remain. The U.S. Energy Information Administration estimates that at least 20 tcf of unproduced coalbed methane proven reserves and unproven resources exist in the San Juan and Raton Basins of New Mexico and Colorado. In addition, over 150 tcf remain untapped in coals across the U.S. For comparison, total natural gas consumption in the U.S. in 2012 was about 25 tcf.

Water Use in the San Juan Basin

Kitty Pokorny and Shari A. Kelley

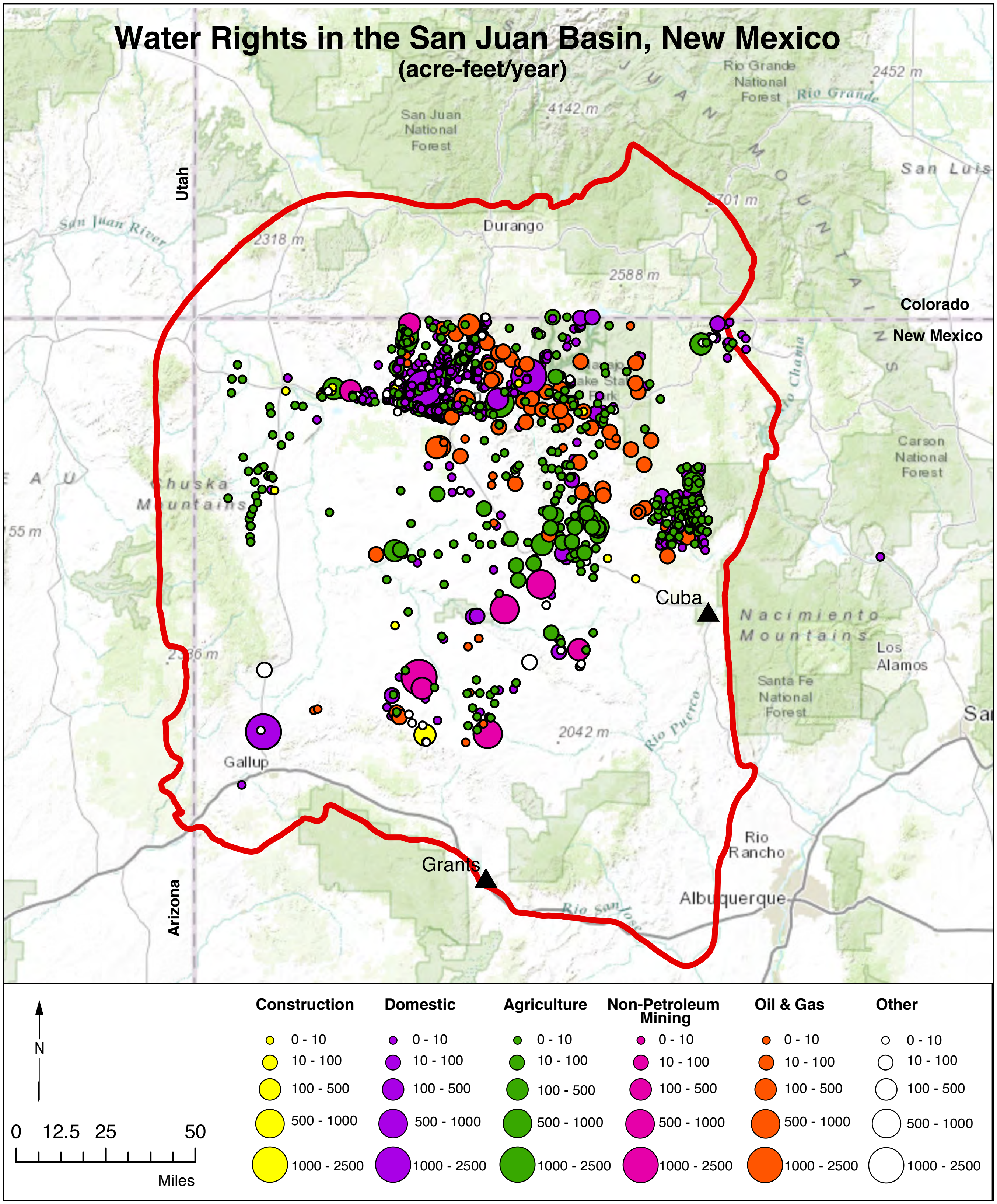


Water rights grouped by category, with breakout for the oil and gas industry. *Data source: Office of the State Engineer.*

Bureau staff are currently assessing the impact of shale gas exploration on groundwater sustainability in the San Juan Basin. Tracking the actual amount of water use in the basin would be very difficult. Instead, we are evaluating the amount of groundwater that could be used in the basin by looking at the water rights/permits that have been allocated to a variety of stakeholders in the San Juan Basin by the Office of the State Engineer (OSE). The basin as defined by the OSE is in the center of the geologically-defined San Juan Basin, and includes parts of four counties in northwestern New Mexico (San Juan, Sandoval, McKinley, and Rio Arriba).

All records for groundwater rights in the San Juan Basin were downloaded from the OSE's online WATERS database into an Excel spreadsheet. A total of 5,059 groundwater records were analyzed. Water rights records with diversion amounts were sorted by use code, and the number of records and the amount of acre-feet per year of water allocated was tabulated for each use. The graph illustrates the distribution by type of use, and the map shows the spatial distribution of the water rights in the San Juan Basin. The largest owners are domestic users and municipalities at 49 percent, mining (coal and uranium) at 21 percent and food production at 19 percent. The petroleum industry (oil and gas) owns 10 percent of the groundwater rights. 70 percent of the rights held by petroleum companies are classified as industrial. Many of these industrial wells were drilled by El Paso Natural Gas in the early 1950s and were sold to Meridian in 1985. That year those wells were either "temporarily abandoned" or were in use and then "held on standby for future water requirements for oil and gas exploration/development drilling." Meridian was purchased by Burlington Northern Resources in 2002. Burlington Northern has since been purchased by ConocoPhillips. Those industrial water rights now appear to belong to ConocoPhillips, although a change of ownership has not yet been filed with OSE. Thus the petroleum industry has water rights that total about 2805 acre-feet/year (afy). For reference, a typical domestic user has rights to 3 afy.

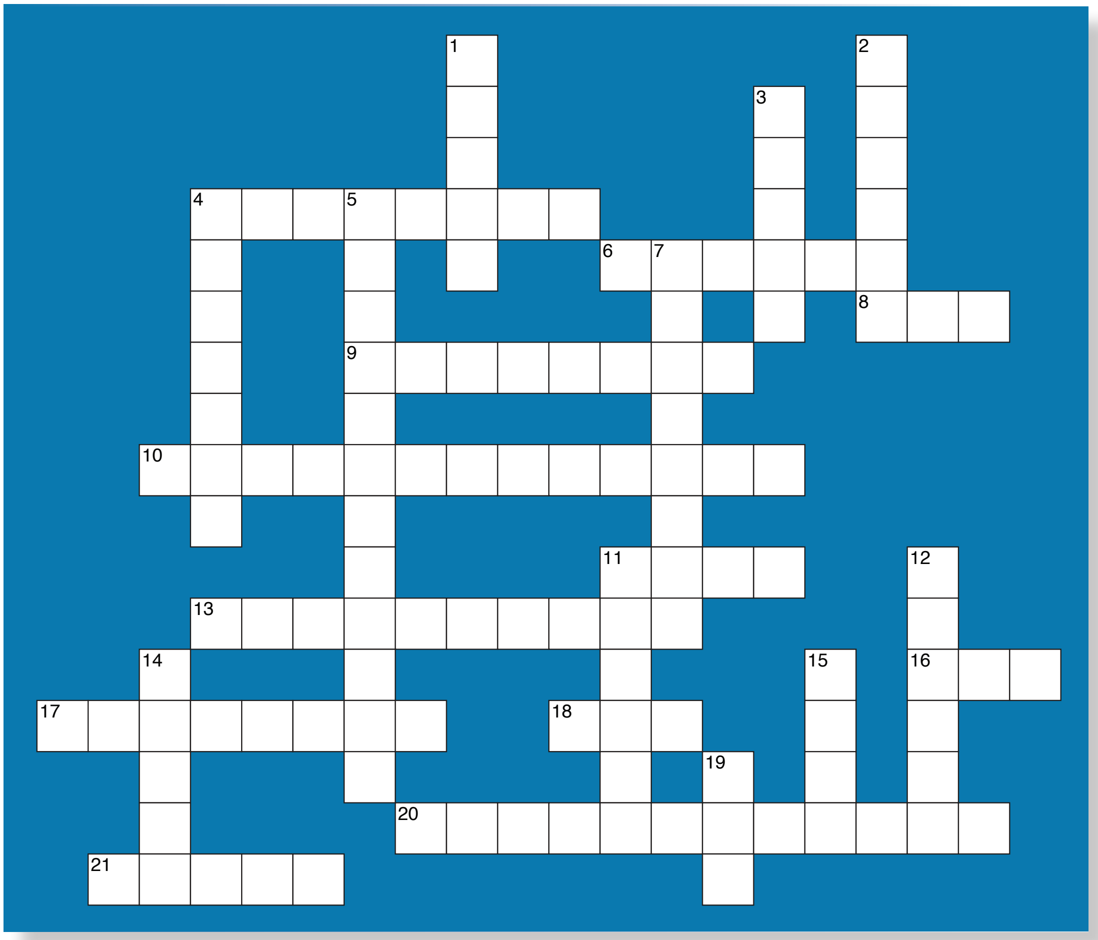
We have also investigated the history of two of the water sources utilized during recent horizontal drilling efforts by Encana, who uses the Dugan water well near the Blanco Trading Post, and WPX and Logos Resources, who use Turtle Mountain Spring near the Escrito Trading Post. The water right associated with the Dugan well, which was appropriated for use as drilling and completion fluids for petroleum exploration in 1982, is 10 afy. This well is an abandoned oil well plugged back to 1073 feet, and it produces from either the Nacimiento Formation or the Ojo Alamo Sandstone. Turtle Mountain "spring" is a series of sumps in the Nacimiento Formation originally developed for irrigation/commercial purposes, with a total right of 213 afy. This water source has been providing water for oil well drilling since 1956. The total amount allocated for commercial use appears to be less than 25 afy.



Spatial distribution of water rights in the San Juan Basin. Colors represent different end users. Size of bubble indicates the size of the allocated water right in acre-feet/yr. *Data source: Office of the State Engineer.*

Oil and Gas Crossword Puzzle

Douglas Bland



ACROSS

4. sand used in hydraulic fracturing is this
6. shale formation member producing oil in New Mexico
8. produced by petroleum wells and cows
9. crack in bedrock
10. enhanced oil recovery technique
11. material used in hydraulic fracturing
13. new type of well
16. shales begin their lives as this
17. hydraulic fracturing
18. liquid petroleum
20. fracturing increases this
21. traditional type of water used in fracturing

DOWN

1. this gets "cooked" into oil and gas
2. this protects aquifers from contamination
3. sedimentary rock with low permeability
4. oil and gas producing basin
5. holes that go through casing
7. conventional type of well
11. one type of water now used in fracturing
12. material pumped between casing and bedrock
14. most common hydraulic fracturing fluid
15. this is drilled to access oil
19. abbreviation for barrel

The answers to the clues are located in the New Technologies in the Oil and Gas Industry article in this issue of *Lite Geology*. **The solution to the puzzle is found on the last page of this issue.**

New Mexico's Most WANTED MINERALS

ANHYDRITE

Virgil W. Lueth

This 4.6" x 3.5" x 2.2" specimen of crystalline anhydrite is from the Naica mine, Chihuahua, Mexico. *Image courtesy of The Arkenstone, photograph by Joe Budd.*

DESCRIPTION: Anydrite is an anhydrous salt of calcium and sulfate ($CaSO_4$), very similar to gypsum in occurrence and appearance. It is colorless to pale blue or violet when found in transparent crystals. Crystals are typically tabular to equant rectangular prisms with a very simple straight termination (pinacoid). Twinning is common, and it has three cleavages. The cubic cleavage is what differentiates it from calcite or gypsum. It has a pearly to greasy luster with certain faces appearing vitreous. Massive varieties are mainly colored by impurities, and can vary from white to mauve, rose, pale brown, or gray. It is most typically massive, granular, nodular, or fibrous. It breaks very uneven to splintery, and tends to be very brittle. It is soft, with a Mohs hardness of 3 to 3.5.

WANTED FOR: Crystalline anhydrite is primarily collected as a mineral specimen, since it is relatively rare at Earth's surface. Otherwise, it can be used in a fashion similar to gypsum for soil treatments, and drying agents in plaster, paint, and varnish. It can also be used for plaster and wallboard. Copious amounts of synthetic anhydrite are produced from the manufacture of hydrofluoric acid (3.5 tons per for every ton of HF), which is used for cement, plaster, flooring, and as fillers in plastics and paper.

HIDEOUT: Anhydrite is very common in the deep subsurface, often encountered while drilling oil wells. This is because gypsum dehydrates at temperatures around 392 degrees Fahrenheight (200 degrees Celsius). Anhydrite is commonly altered to gypsum ($CaSO_4{\cdot}2H_2O$) by groundwater, so it is rarely seen at Earth's surface. It can form in special surface environments where excess sodium or potassium chloride is present and the temperature of the water is above 104 degrees Fahrenheight (40 degrees Celsius). It can also form in tidal flats in desert environments as nodules. Salt domes, which are not found in New Mexico, also contain a caprock of anhydrite formed by the interaction of oil, gypsum, calcite, water, and hydrogen sulfide. The mineral also forms in some ore deposits under hydrothermal conditions.

LAST SEEN AT LARGE: New Mexico is famous for the large deposits of anhydrite in the subsurface of the southeastern portion of the state. It is commonly found in deep wells in Chaves, Eddy, and Lea Counties. It is also reported in the San Andreas Mountains and Sierra Oscura in Sierra and Socorro Counties, respectively. It is also reported in the ore deposits of the Mogollon district (Catron County), Tijeras district (Bernalillo County), and Capitan and White Oaks districts of Lincoln County. It is commonly associated with halite, calcite, dolomite, and gypsum making it hard to identify since they are all very similar in appearance.

ALIASES: The mineral was given its name in allusion to its lack of water by A. G. Werner. Other names include: vulpinite, tripestone, cube spar, karstenite, and muriacite.

New Mexico's Enchanting Geology

Stacy Timmons

WHERE IS THIS?

Sitting Bull Falls, Sitting Bull Canyon, Eddy Co., New Mexico. Close-up shows travertine deposits with open holes and molds that once held plant matter. *Photos courtesy of Peter Scholle.*

Located in the Lincoln National Forest about 30 miles southwest of Carlsbad, New Mexico, Sitting Bull Falls Recreation Area is a spring-fed waterfall area managed by the U.S. Forest Service. This is a day-use only area, with picnicking, hikes through spectacular scenery, restrooms, and the feature of the park—natural pools and a waterfall. In an area where water is rare, Sitting Bull Falls is an oasis that is well worth the drive.

While the park's name is a bit of a misnomer (Sitting Bull was never actually there!), the water and geology of this park keep it interesting. All around this area, oil and gas wells tap into deeper layers of Permian age rocks (approximately 250 million years old). Here, other Permian units, including the Grayburg and San Andres Formations produce fresh, cool spring water. As the water, which is saturated with calcium bicarbonate and carbon dioxide, discharges from the ground, it flows about one mile before dropping over the waterfall. As the water pours over the cliff and releases carbon dioxide, calcium carbonate (here known as travertine or tufa) precipitates. Small plant and other organic debris may become coated in this travertine, and then later rot away leaving behind open spaces in the travertine. The pools at this area provide an opportunity to cool off and examine the unique texture of the travertine. There is also a small cave hidden behind the waterfall, however access can be very slippery!

The recreation site is temporarily closed due to flood damage sustained in September 2013. The site should be open by early 2015. Please contact the Guadalupe Ranger District Office of the Forest Service at (575) 885-4181 for information about re-opening.

 By Janet Bruelhart, Science Teacher, Lovington High School

The Removal of Copper from a Carbonate

Malachite is a copper carbonate hydroxide that is a secondary mineral found in oxidation zones of copper deposits found in New Mexico. It has a distinctive green color compared to azurite, which is blue. Malachite is considered to be a minor copper ore and is most prized for its use as a gemstone. The copper in malachite can be extracted by several methods. The laboratory exercise presented here demonstrates some important chemistry principles including oxidation and reduction, the activity series of metals (a ranking of their relative reactivity), and types of reactions. Here is an introduction to the lesson. The full lesson including materials list, procedures, and data and observation sheets can be found at the following link: **http://geoinfo.nmt.edu/education/exercises/home.html**

Teacher Background:

The chemical formula for malachite is $Cu_2CO_3(OH)_2$. When malachite is heated, carbon dioxide gas and water vapor are released and copper (II) oxide remains along with any impurities found in the mineral. In chemistry class, copper (II) carbonate can be used to model the decomposition of malachite. There are similarities in the formulas of each; copper (II) carbonate is $CuCO_3$, and malachite is a basic form of copper (II) carbonate with OH- ions attached. The equation for the decomposition of the copper (II) carbonate is:

$CuCO_{3(s)} \rightarrow CuO_{(s)} + CO_{2(g)}$ **(decomposition)**

In these equations (s) denotes a solid, (g) denotes a gas, (aq) denotes an aqueous solution, and (l) denotes a liquid. The equation for the decomposition of malachite is almost the same, except that water vapor is also a product.

$Cu_2CO_3(OH)_{2(s)} \rightarrow 2CuO_{(s)} + CO_{2(g)} + H_2O_{(g)}$
(decomposition)

In this experiment, a bead of malachite will be crushed and heated in a crucible to form the copper (II) oxide, which will then be treated with sulfuric acid in a double replacement reaction, resulting in a deep blue copper (II) sulfate solution as follows:

$CuO_{(s)} + H_2SO_{4(aq)} \rightarrow CuSO_{4(aq)} + H2O_{(l)}$
(double replacement)

The blue copper (II) solution is collected, and finally, freshly sanded iron nails are added to the copper (II) sulfate and allowed to rest overnight. A single replacement reaction results in pure, elemental copper being deposited onto the iron nails as follows:

$CuSO_{4(aq)} + Fe_{(s)} \rightarrow FeSO_{4(aq)} + Cu_{(s)}$ **(single replacement)**

Notes:

A quantitative analysis is possible by using the pure copper (II) carbonate and taking precise measurements of mass before heating and after heating to calculate the amount of carbon dioxide released. The amount of copper in the resultant copper (II) oxide can be determined stoichiometrically and compared to the theoretical yield. Those calculations can be used to determine the percent error.

This lab can also be adapted to be more inquiry-based for a beginning chemistry class as a lab on types of reactions by removing the equations and having students predict the products when given only reactants. Prior knowledge of polyatomic ions and types of reactions would allow the students to write their own chemical equations as three different types of reactions are done.

Preparation:

Supplies are found in general chemistry labs. Malachite beads are easily obtained from online sources or mineral shops. The 8mm beads are placed inside a plastic bag and crushed with a hammer. They are then ground further with a mortar and pestle.

Use caution with sulfuric acid. Goggles and aprons must be worn by all. When heating crucibles with a Bunsen burner, students must realize that very high temperatures are achieved, and there is a risk for burns. Open flames must be respected with caution.

Malachite specimen from the Buckeye Mine, Magdalena district, Socorro County, New Mexico. Bureau of Geology museum specimen #9858. *Photo courtesy of Debra Wilson.*

profile of a new mexico earth science teacher

Janet Bruelhart teaches chemistry and biology at Lovington High School. She was born and raised in California. Her parents were new immigrants from Switzerland who arrived in this country after World War II. She did not speak english until she started school because the family spoke Swiss german at home. Janet was the oldest of five daughters in a family of dairy farmers, and she grew up feeding calves, milking, and working outside.

After earning a Bachelor of Science degree in Plant Pathology and a Master of Science degree in Agriculture, Janet went to Switzerland to work at a research facility for animal production, where she met her husband, Bruno. In 1982, Janet and her husband became partners with her parents on the dairy farm in California.

Janet and her husband moved their five children and dairy farm to Hobbs, New Mexico in 1991 because it was more economical to expand the farm there. She believed she would always be a dairy farmer because the family could work together doing something they loved. When agriculture became difficult through 2000 and the children headed to college, they sold their interest in the dairy. Her husband became a manager for another 6,000 cow dairy, and Janet started teaching.

Educational background:

Associate of Science, Cottey College, 1977

Bachelor of Science, Plant Pathology, University of California-Davis, 1979

Master of Science, Agriculture, California Polytechnic University-San Luis Obispo, 1980

Awards and recognition:

Secondary Teacher of the Year, Lovington Municipal Schools (2005, 2013)

Science Olympiad Coach of the Year, Division C (2007, 2013)

Donley Excellence in Education Award (2010)

New Mexico Golden Apple Fellow (2008)

How do you include Earth Science in the chemistry curriculum? Earth Science is easy to incorporate into chemistry because of the elements that we discuss, along with their physical and chemical properties. I teach about the periodic table and the discovery of the elements. This leads to lessons on the formation of ores within the Earth and other topics such as volcanism, plate tectonics, and so on.

Janet Bruelhart is standing on tilted ash beds on the Sevilleta National Wildlife Refuge at the *Rockin' Around New Mexico* workshop in 2013. *Photo courtesy of Janet Bruelhart.*

Chemistry is important in the deposition of desired metals and minerals, which are refined for our use. Rare earth elements are in the news because of their demand in today's technological devices. All of these elements and compounds come from the Earth, which most students do not realize. A similar belief is that the source of milk is the grocery store.

Why did you become a science educator? I decided to teach because my children were in Science Olympiad, and I saw a need as I helped them with their events. I took necessary classes for certification, did my student teaching, and was hired as a middle school teacher in Lovington. After two years, I was asked to teach chemistry at Lovington High School because of my college chemistry background. I was very intimidated by the subject, but refreshed my skills and jumped into the chemistry classroom. I love my job. I love the chemistry, and I love the students. We work hard together, and I have very high expectations from each student. Every day is a work day in my classroom, and students make an effort to be in class and learn. Students think I am so smart and know everything, which is very humbling. In reality, I know very little, but I am interested in everything. This job is very fulfilling. I hope to make a difference in the lives of my students by exemplifying a solid work ethic and a thirst for knowledge.

Advice or suggestions for other Earth Science teachers: Be an explorer. Teachers in New Mexico have the best professional development opportunity in *Rockin' Around New Mexico.* Through this program I have seen places I did not know existed in this state. Because of this workshop I have become more aware of the beauty and diversity of the state, its rocks and minerals, geologic features, and geologic history. It is led by professionals in the field, and I have learned to look more closely and understand more fully what the Earth presents as I travel around the United States and abroad. Look, explore, listen, and learn, always.

Favorite lesson in Earth Science:

Extraction of Copper from Malachite—I use a copper mineral to explore an important chemistry topic: redox chemistry. Students learn about oxidation and reduction, the activity series of metals (a ranking of their relative reactivity), and types of reactions. The experiment involves the extraction of copper from the mineral malachite, using an ancient smelting method that early man may have used, according to some historians. Students must make percent composition calculations as well as identify the reduction and oxidation of the copper compounds. This lab is done late in the school year because it involves many principles of chemistry and requires patience as the reduction phase takes much time.

This lab utilizes malachite or copper carbonate. The mineral is crushed and heated to form copper (II) oxide, which is then dissolved in sulfuric acid to form copper (II) sulfate, which in turn is reduced using iron nails in a redox reaction to form the copper. This lab is explained in more detail in the previous article, and at the following link http://geoinfo.nmt.edu/education/exercises/home.html. An alternative method is to reduce the copper (II) oxide using charcoal to form solid copper. Either lab can be modified to the appropriate skill level of students ranging from middle school through AP Chemistry.

When did you fall in love with geology? I became passionate about geology after we moved to New Mexico. I helped students with rocks and minerals for Science Olympiad. I discovered the summer geology workshop *Rockin' Around New Mexico*, which became the focal point of my summers so I could learn and have fun at the same time. I love the wealth of knowledge presented, and though I teach chemistry, that geology knowledge has been incorporated into my chemistry classes.

What hobbies do you have that relate to your science teaching? I have become a rock and mineral collector. I love being outdoors, hiking, and exploring the road less taken. I fill my backpack with rocks whenever it is permissible to collect on a hike. I especially look for copper ores to incorporate into electrochemistry. I rely on my experience as a dairy farmer to teach about bovine nutrition, reproduction, and physiology in biology. Even my yard work relates to biology lessons. I also bring my travel experiences back to the classroom. Our family travels to Switzerland to visit relatives. I have logged more than 140 miles on scout backpacking treks, and I have canoed more than 50 miles at Northern Tier Scout Ranch in Canada. I have hiked the Inca Trail near Machu Picchu in Peru, and fished for piranha on the Amazon. In class, I create test questions and develop problems based upon my experiences on the trail, in a canoe, on the dairy, in my yard, or in the rainforest.

Janet Bruelhart is with her husband Bruno on a hike in the Swiss Alps. Janet's son Alex introduces himself to a Brown Swiss cow. All of the cows wore bells and were on their annual parade from the foothills to the high summer pastures for a different type of grass to eat. The milk produced in the mountains is made into Alpine cheese. *Photos courtesy of Janet Bruelhart.*

What is your favorite geologic feature in New Mexico? One of my favorite places in New Mexico is the Jemez region and the Valles Caldera. The rock exposures in the canyons of the Jemez and the caldera are fascinating. Visiting that region and knowing its geologic history made my trip to Crater Lake in Oregon even more exciting because I was able to compare volcanic features and formations.

What are your favorite web links for science resources?

Biology Junction is a website that has resources for any biology class including labs, outlines, diagrams, and activities. The main page for Biology Junction is found at: **http://www.biologyjunction.com/**

Chemmybear provides information that I use in AP Chemistry. It includes activities for students and practice questions that are useful for preparation for the AP Chem exam. Visit this site at: **http://www.chemmybear.com/**

Earth Briefs—March 10, 2014 Socorro Earthquake!

Douglas Bland and Susan Welch

If you have lived in Socorro, New Mexico for a long time, you probably have experienced earthquakes, maybe including the one that struck just after 9 p.m. on March 10, 2014. While there was no damage, it was felt from Lemitar to San Antonio. The U.S. Geological Survey measured the quake at magnitude 3.3. The epicenter was located about six miles southeast of Socorro, at a depth of two to three miles.

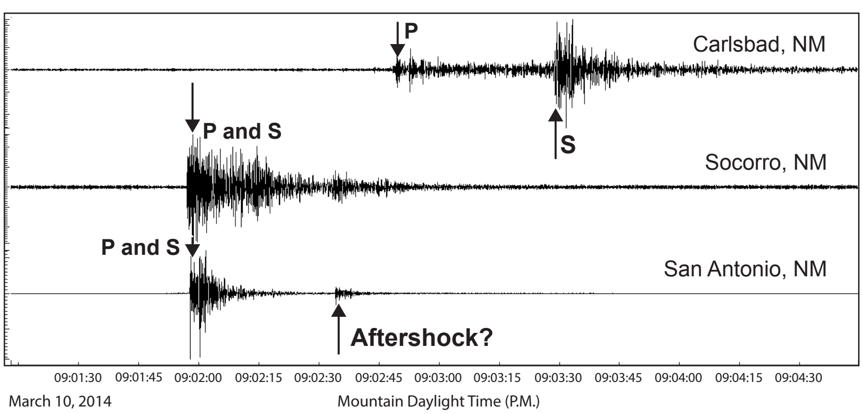
Large earthquakes are uncommon in New Mexico, but small ones occur frequently, with almost half of them concentrated in a small area around Socorro. Most of them, including the recent one, are related to a magma body about 11 miles deep that underlies this region. Here, magma is being injected through a conduit from the molten mantle below. This creates stress on the overlying brittle rocks, which break and cause earthquakes. See the Socorro Magma Body article in Issue 31 of Lite Geology:
http://geoinfo.nmt.edu/publications/periodicals/litegeology/31/lite_geo_31spring12.pdf

Susie Welch conducted a non-scientific survey of local residents (about 35 responses) to determine what type of earthquake effects were noticed in the area between Socorro and San Antonio. Interestingly, noise was as common as Earth and structure movement. Generally, the quake was felt strongest by people living nearest to the Rio Grande. The most extreme effects were experienced by residents living south of Socorro in Bosquecito and Luis Lopez, communities closest to and directly west of the epicenter of this event. These people reported multiple loud and intense booms or shocks, which reminded them of explosions, and had more severe shaking of structures.

Most people reported rumbling and shaking. People in neighborhoods near New Mexico Tech, which are farther from the river and the epicenter, said they didn't notice violent shocks or loud sounds as much. A few commented that their pets were disturbed by the shaking. Thankfully the sleeping baby in the household in Bosquecito, closest to the epicenter, was not awakened!

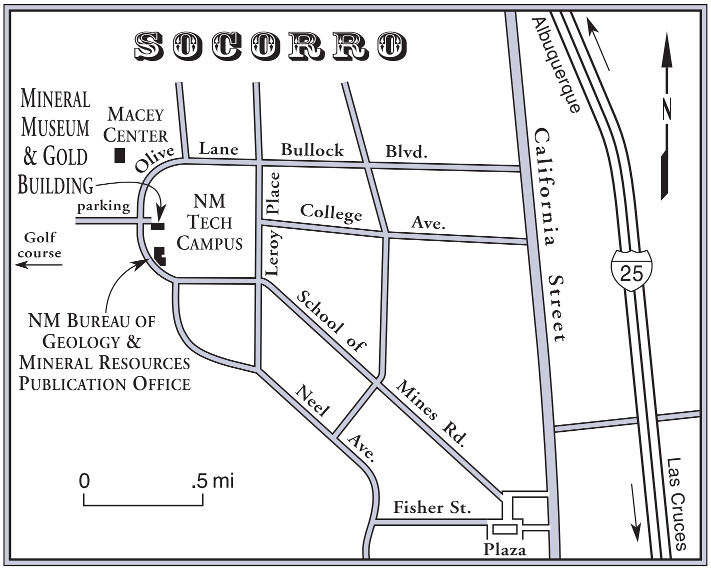
Here are a few comments from local residents:

- I live in an RV. It felt like I was on a boat rocking.
- We heard 2 "booms" much like sonic booms…then one much stronger BOOM that actually shook the house…
- There was a small jolt, then it felt like a rumbling. Like a train going by. I heard a huge boom! The noise was much more jarring than the shaking. I thought it was a terrible explosion at first.
- There was a deep rumbling noise first, then shaking for about four seconds. Dogs started barking and jumped around like someone was at the door.
- I was sitting at a desk, typing at a computer. I felt a rolling rumble, then a few seconds later heard something like an electrical pop.



Seismometer recordings of the March 10, 2014 Socorro earthquake. Note the different character of the traces from different locations. Earthquakes cause movement of rock to spread out in two main types of waves. P waves move much faster than S waves. It took about 50 seconds for the P wave to reach Carlsbad, and another 40 seconds for the S wave to arrive. However, Socorro and San Antonio are so close to the epicenter that both waves were recorded almost simultaneously and are difficult to separate. A small probable aftershock about 40 seconds after the main quake was registered in the Socorro and San Antonio recordings, but was not obvious in Carlsbad. *Data courtesy of the New Mexico Seismological Observatory.*

Short Items of Interest to Teachers and the Public



THE MINERAL MUSEUM ON THE CAMPUS OF NEW MEXICO TECH IN SOCORRO, NEW MEXICO

Hours:

8 a.m. to 5 p.m., Monday through Friday

10 a.m. to 3 p.m., Saturday and Sunday

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The Mineral Museum is located in the Gold Building on the campus of New Mexico Tech in Socorro. The bureau's mineralogical collection contains more than 16,000 specimens of minerals from New Mexico, the United States, and around the world, along with mining artifacts and fossils. About 2,500 minerals are on display at a time.

For teachers, students, and other groups, we offer free tours of the museum. We like to show off our home state minerals, as well as give students an idea of how minerals end up in products we use every day. Museum staff can also identify rocks or minerals for visitors. Please call ahead to ensure someone will be available. For more information on the museum, please visit our website at: **http://geoinfo.nmt.edu/museum/**

Dr. Virgil W. Lueth (575-835-5140)
Senior Mineralogist and Curator
vwlueth@nmt.edu

To Schedule a Museum Tour, Contact:

Susie Welch (575-835-5112)
Manager, Geologic Extension Service
susie@nmt.edu

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UPCOMING EVENTS FOR TEACHERS AND THE PUBLIC

Rockin' Around New Mexico
July 8-11, 2014
Silver City, New Mexico

This summer our annual teacher workshop, *Rockin' Around New Mexico* will be located in Silver City. We will explore the complex geologic story of the Silver City area, including the history of the formation of porphyry copper deposits. Field trips will include a tour of the Chino copper mine and ore processing facilities, and stops at various locations where teachers will explore faults and volcanic features. The workshop will conclude with instruction on seismic hazards and school safety in New Mexico. The 3-day workshop is for active K–12 classroom teachers or pre-service teachers. A one-hour graduate credit is available through the Master of Science for Teachers (MST) at New Mexico Tech. Interested teachers should contact Susie Welch at 575-835-5112, or **susie@nmt.edu**.

Earth Science Week
October 12-18, 2014

This year, Earth Science Week will promote awareness of the dynamic interactions of the planet's natural and human systems with a theme of "Earth's Connected Systems." The goal of Earth Science Week in 2014 is to engage people of all ages in exploring the ways that Earth Science illuminates natural change processes. This knowledge helps us deepen our understanding of interactions of Earth systems: the geosphere, hydrosphere, atmosphere, and biosphere. Explore ways in which you can participate in Earth Science Week by visiting the website at: **http://www.earthsciweek.org/**

Study Guides

The Office of Fossil Energy, under the U.S. Department of Energy, provides Fossil Fuel Study Guides for Secondary Students on its website. Here are the links for several study guides at various grade levels:

High School Fossil Energy Study Guide: Oil
http://energy.gov/sites/prod/files/2013/04/f0/HS_Oil_Studyguide_draft2.pdf

High School Fossil Energy Study Guide: Coal
http://energy.gov/sites/prod/files/2013/04/f0/HS_Coal_Studyguide_draft1.pdf

Middle School Fossil Energy Study Guide: Coal
http://energy.gov/fe/downloads/coal-study-guide-middle-school

Elementary School Fossil Energy Study Guide: Coal
http://energy.gov/sites/prod/files/Elem_Coal_Studyguide.pdf

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SOLUTION TO CROSSWORD PUZZLE