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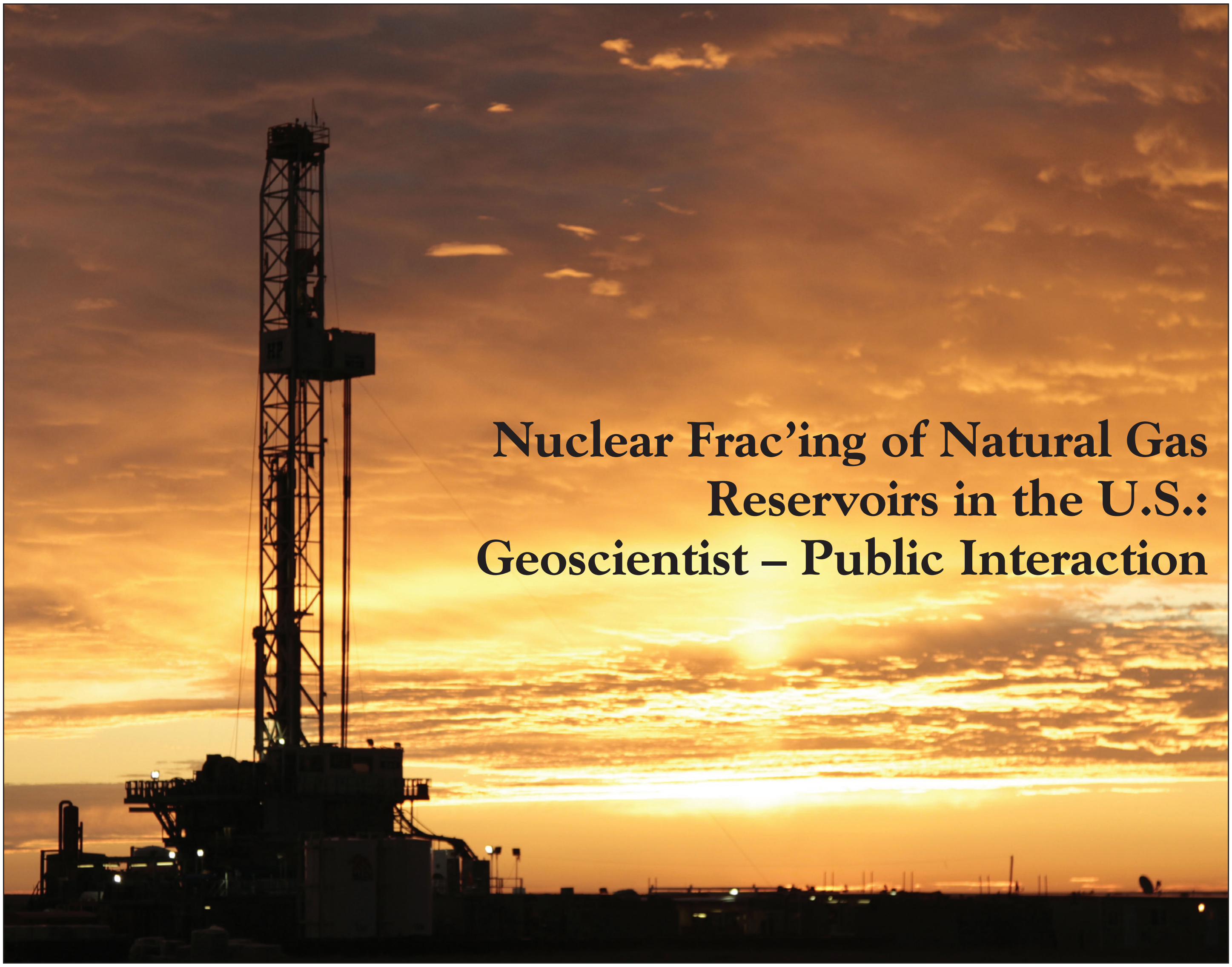
Nuclear Frac'ing Of Natural Gas Reservoirs In The U.S.:
Geoscientist – Public Interaction,

And Much More.

By: Neil H. Suneson, Oklahoma Geological Survey, Mewbourne College of Earth and Energy, The University of Oklahoma | nsuneson@ou.edu



Nuclear Frac'ing of Natural Gas Reservoirs in the U.S.: Geoscientist – Public Interaction

INTRODUCTION

Most individuals associate the Cold War with the nuclear arms race between the United States and the Soviet Union, but few are aware that, at the same time, an effort was made by both countries to use nuclear explosions for peaceful purposes (Project Plowshare in the U.S.), and few geologists are aware that a significant effort was made to fracture-stimulate tight, low-permeability gas-bearing sandstones. This paper reviews the history of the Plowshare gas wells in the context of the Cold War and subsequent anti-nuclear sentiment and rise of environmentalism in the country (Figure 1) and asks if there are any lessons to be learned that can be applied to the "anti-frac'ing" movement today. How did geologists and engineers in the late 1960s and early 1970s address public concerns about nuclear frac'ing, are similar concerns being raised today, and are we responding to them?

When the Cold War began and ended is a matter of debate, but Winston Churchill's speech on March 5, 1946, at Westminster College in Fulton, Missouri, where he introduced the term "iron curtain," is a convenient beginning. Only seven months before that speech the U.S. had destroyed Hiroshima and Nagasaki, Japan, bringing World War II to a quick end. Four months after the speech the U.S. conducted its first post-war nuclear weapons test on Bikini Atoll in the Marshall Islands in the western Pacific Ocean. For the next 46 years the U.S. and U.S.S.R. conducted 1747 nuclear tests on land, under water, in the atmosphere, and in space, with the vast majority being weapons tests. Other countries, most notably France, also conducted nuclear tests (Figure 2). The end of the Cold War might be marked by the fall of the Berlin Wall in November 1989; alternatively, the last Soviet nuclear test in 1990 or last U.S. test in 1992 might serve as a suitable date.

NUCLEAR EXPLOSIONS - BASICS

Two kinds of nuclear reactions provide the explosive force necessary for weapons and peaceful uses – fission and fusion. Nuclear fission reactions occur when a mass of fissile material (typically ^{235}U or ^{239}Pu) (U – uranium; Pu – plutonium) becomes supercritical and neutrons, which are produced as a result of spontaneous decay but typically escape from the mass, instead induce fission. Each fission reaction produces daughter products (lighter elements), more neutrons, gamma rays, and energy (Figure 3A). If the ^{235}U or ^{239}Pu is supercritical, the emitted neutrons produce more fission reactions and even more neutrons, gamma rays, and energy, producing a chain reaction and an explosion. A critical feature of the explosive device, be it a bomb or part of a drill string in a wellbore, is that it remain intact as long as possible so a maximum or predicted amount of supercritical fuel is fissioned. (Less than 1.6% of the enriched uranium in the Little Boy bomb that exploded over Hiroshima fissioned because the bomb fragmented.) Weapons that rely on fission as their sole source of energy are known as atomic bombs or A-bombs, for short.

Nuclear fusion reactions involve the combining (or fusing) of two isotopes of hydrogen (deuterium – ^{2}H and tritium – ^{3}H) to form helium (^{4}He) (Figure 3B.). This reaction also produces energy and a neutron. Most fusion explosions start with a fission reaction that compresses and heats the fusion fuel which reacts forming helium, producing energy, and releasing neutrons, which causes additional fission reactions. Weapons that rely partly on fusion reactions are known as hydrogen bombs, H-bombs, or thermonuclear bombs.

The underground nuclear explosions that would be used to fracture tight-gas sandstones in the western U.S. as part of Plowshare produced radioactive isotopes, and the nature and amount of isotopes varied depending on the type of explosive device used (fission or fusion) and the composition of the rock that was being fractured (Toman and Tewes, 1977; Terman, 1973). Most of the radioactive isotopes were concentrated in the melted rock that formed a glass puddle at the bottom of the chimney (described below), on the surfaces of the rock fragments, or in the voids in the chimney. The most critical contaminant isotopes from a potentially producible natural gas perspective were the gas ^{85}Kr (Kr – krypton) and tritium (incorporated into the hydrocarbon and produced water). The first nuclear fracture-stimulation event, known as Gasbuggy, used a fusion explosive device. The two next events – Rulison and Rio Blanco – used fission devices and produced much less tritium than Gasbuggy.

PLOWSHARE

Project Plowshare was a U.S. government-sponsored program to develop peaceful uses for nuclear explosives (USDOE, 1997). The concept of using nuclear energy for peaceful purposes was conceived at about the same time the U.S.'s first nuclear test – Trinity – was being developed but gained prominence immediately after the devastation in Hiroshima and Nagasaki at the end of World War II. In June 1946, the U.S. proposed the Baruch Plan to the United Nations Atomic Energy Commission. It would ban the possession (in the case of the U.S.) and prohibit the development (all other countries) of nuclear weapons and would promote the exchange of nuclear information and technology for peaceful purposes. The Soviet Union rejected the proposal because it felt the U.N. was controlled by the U.S. and its allies and would not deal with information exchange and inspections fairly. As a result of the Soviet rejection, the U.S. Atomic Energy Commission (AEC), which was created by Congress as part of the Atomic Energy Act of 1946 and given unprecedented powers – "complete and exclusive control over ownership, production, and use of all atomic material, whether civilian or military" (Kreith and Wrenn, 1976, p. 3) – focused on weapons development. It would be ten years before a formal project to develop peaceful uses for nuclear explosives would be established.

Project Plowshare was established by the AEC in early 1957 but was publicly announced later, in 1958, because of the secrecy surrounding all U.S. nuclear-research efforts. All of the nuclear tests that were part of Project Plowshare took place during the depths of the Cold War. The project name was taken from Isaiah 2:4 ("And he shall judge among the nations, and shall rebuke many people: and they shall beat their swords into plowshares, and their spears into pruning hooks: nations shall not lift up sword against nation, neither shall they learn war any more"). A number of proposed projects had direct geological applications, including several that included the stimulation of tight-gas reservoirs – Gasbuggy (1967), Rulison (1969), Rio Blanco (1973), Wagon Wheel (not executed), Wasp (not executed), and Dragon Trail (not executed).

Other direct and indirect geological applications of nuclear explosions included:

- rubblizing ore deposits (especially porphyry copper) for *in situ* leaching operations;
- stripping of overburden over mineral deposits;
- storage of water in rubble chimneys;
- storage of gas in rubble chimneys;
- accelerating groundwater recharge and connecting aquifers;
- *in situ* retorting of oil shale deposits;
- development of tar sands in Alberta;
- adding water to hot broken rock in chimneys to produce steam for geothermal energy; and
- fracturing of hot dry rock for geother-

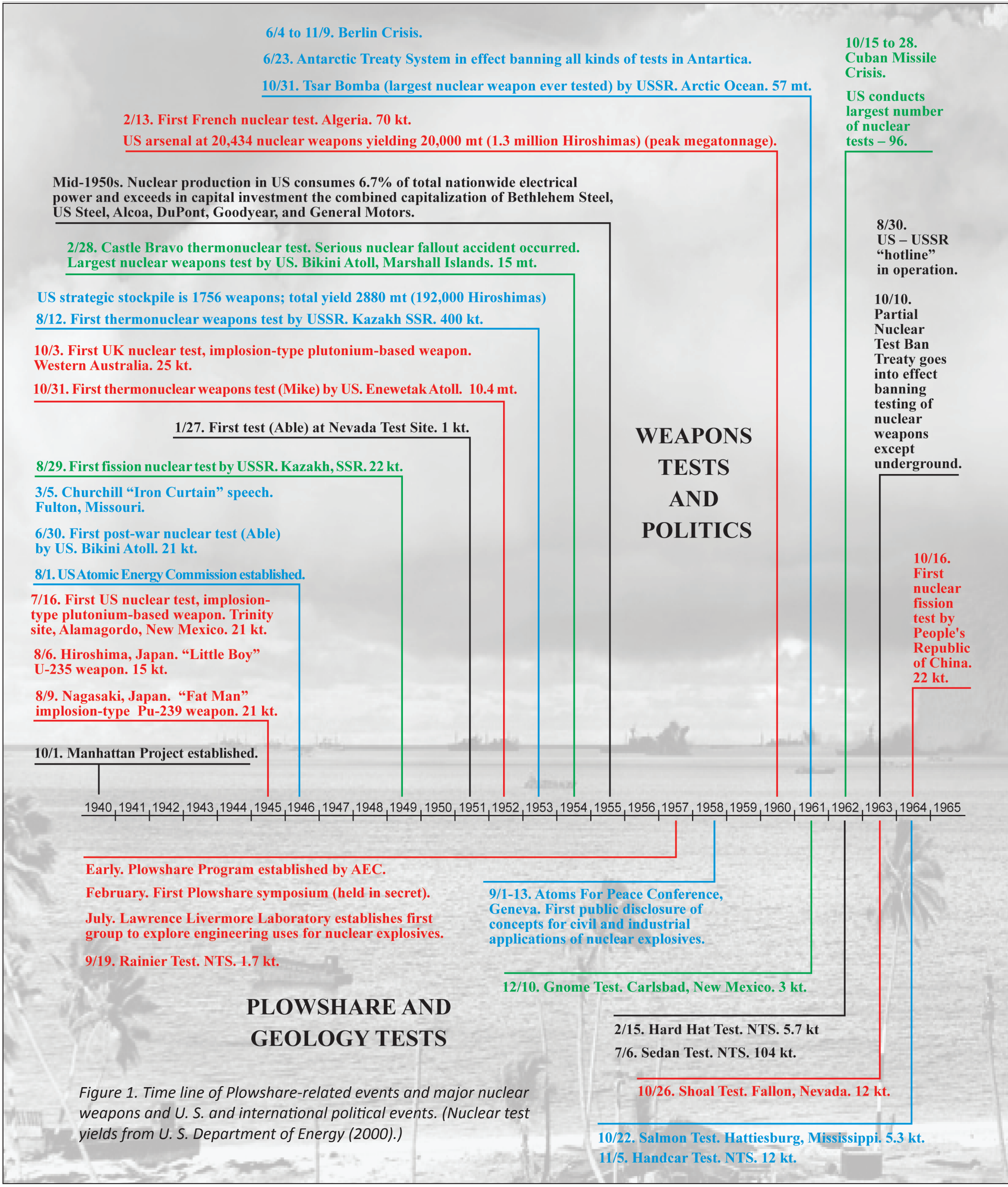


Figure 1. Time line of Plowshare-related events and major nuclear weapons and U. S. and international political events. (Nuclear test yields from U. S. Department of Energy (2000).)

US nuclear stockpile peaks at 31,700 bombs and warheads.

6/6 to 9/1. Oil Embargo following Six-Day War.

6/17. First thermonuclear weapons test by PRC. 3.3 mt.

10/10. Outer Space Treaty goes into effect.

4/22. Treaty of Tlatelolco goes into effect banning testing in South America and the Caribbean Sea islands.

8/24. First thermonuclear weapons test by France. Fangataufa Atoll. 2.6 mt.

Castle Bravo, largest nuclear weapons test by US, 1954.

1/1. National Environmental Policy Act of 1969 goes into effect

3/5. Nuclear Non-Proliferation Treaty goes into effect banning proliferation of nuclear technology to non-nuclear nations.

5/18. Seabed Arms Control Treaty goes into effect banning use of nuclear weapon in international waters.

8/3. Anti-Ballistic Missile Treaty signed (goes into effect in 1990) prohibiting underground testing of more than 150 kt.

10/16 to 3/17/74. Oil Embargo following Yom Kippur War.

7/3. Threshold Test Ban Treaty signed.

5/18. First fission nuclear test by India. NW India. 12 kt.
6/18. Salt II Treaty signed.

9/23. Last US nuclear test (of 1032). NTS. 20 kt.

10/24. Last USSR nuclear test (of 715).

11/9. Berlin Wall falls.

1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992

9/30. Plowshare Program ends.

5/17. Rio Blanco Test. Rifle, Colorado. 3 devices, 33 kt each.

9/10. Rulison Test. Grand Valley, Colorado. 40 kt.

12/10. Gasbuggy Test. Farmington, New Mexico. 29 kt.

Rulison underground nuclear test site, 1969.

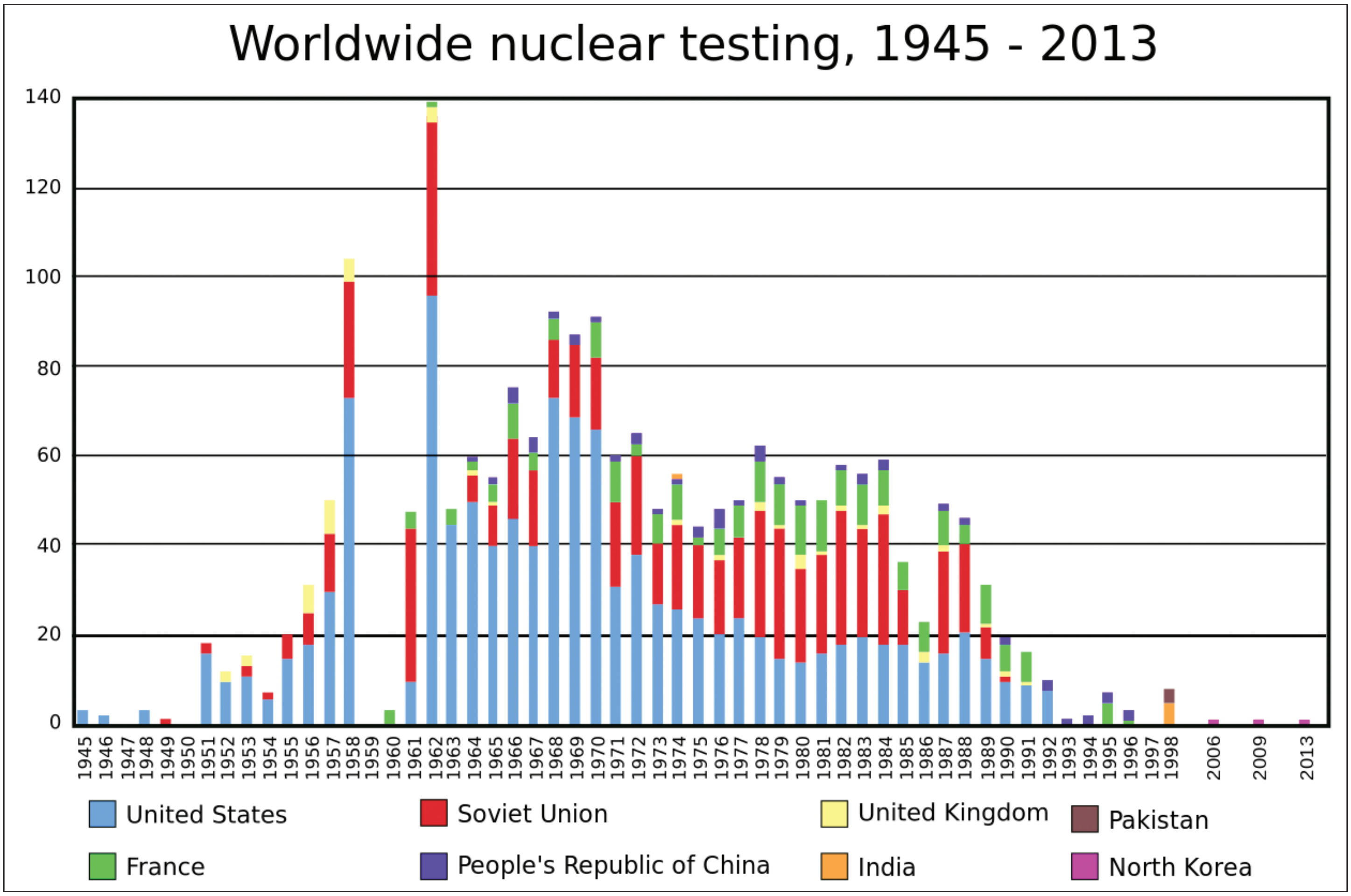


Figure 2. Worldwide nuclear testing (1945-2013) by country. Number of tests on y-axis (from http://en.wikipedia.org/wiki/Nuclear_weapons_testing).

mal energy applications.

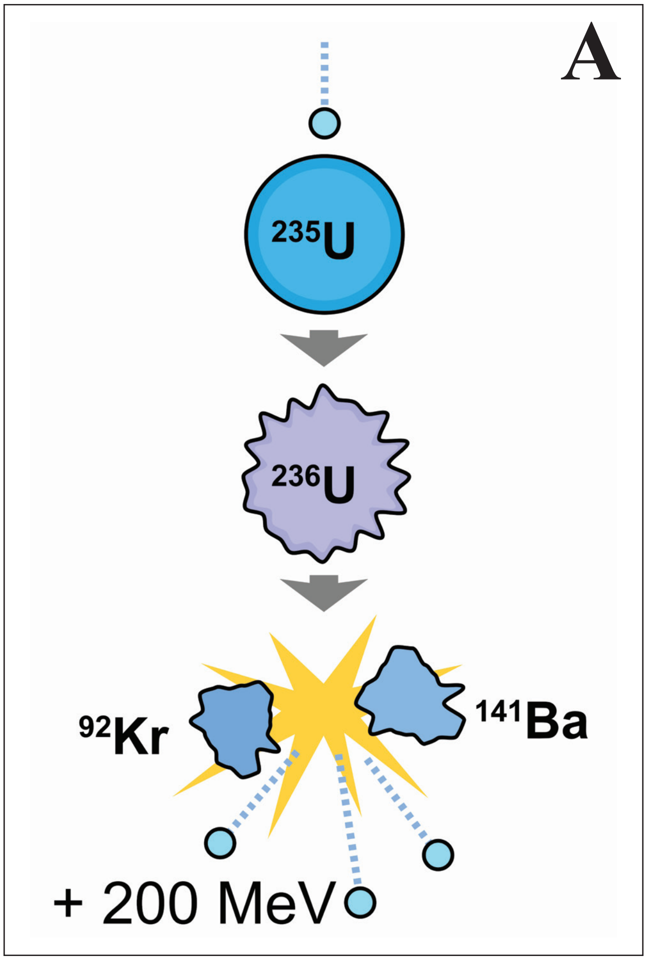
Many of these ideas were proposed as formal Plowshare projects (USDOE, 2000).

Non-geological proposals centered around excavating, such as using nuclear explosions to create harbors and a second waterway connecting the Atlantic and Pacific Oceans through Nicaragua; blasting through mountains for highways, railroads, and waterways; and re-routing river systems. Twenty-seven Plowshare nuclear tests were conducted between 1961 and 1973 (USDOE, 2000); all but four (Gnome, Gasbuggy, Rulison, Rio Blanco) were conducted at the Nevada Test Site (NTS) and of those four three were attempts to develop tight-gas sandstones.

In addition to the Plowshare nuclear tests, some geological studies that followed a number of weapons tests contributed to the attempts to develop tight-gas sandstones using nuclear explosives.

PRE-GASBUGGY NUCLEAR GEOLOGICAL TESTS

Although it was designed as a weapons test, the Rainer shot on September 19, 1957, provided the first data on what an underground nuclear explosion would do to the surrounding rock. The test was the first U.S. underground nuclear explosion and was carried out because fallout from atmospheric tests was becoming a public concern. The 1.7 kiloton (kt) explosive was detonated in bedded tuff 900 ft deep beneath Rainier Mesa at the NTS (Johnson et al., 1959). After the detonation, drillhole cores were collected and analyzed and two drifts were driven into the blast zone. Investigators discovered that a cavity had formed and had subsequently filled with collapse blocks from the roof (Figure 4). The base of the cavity was lined with radioactive quenched glass



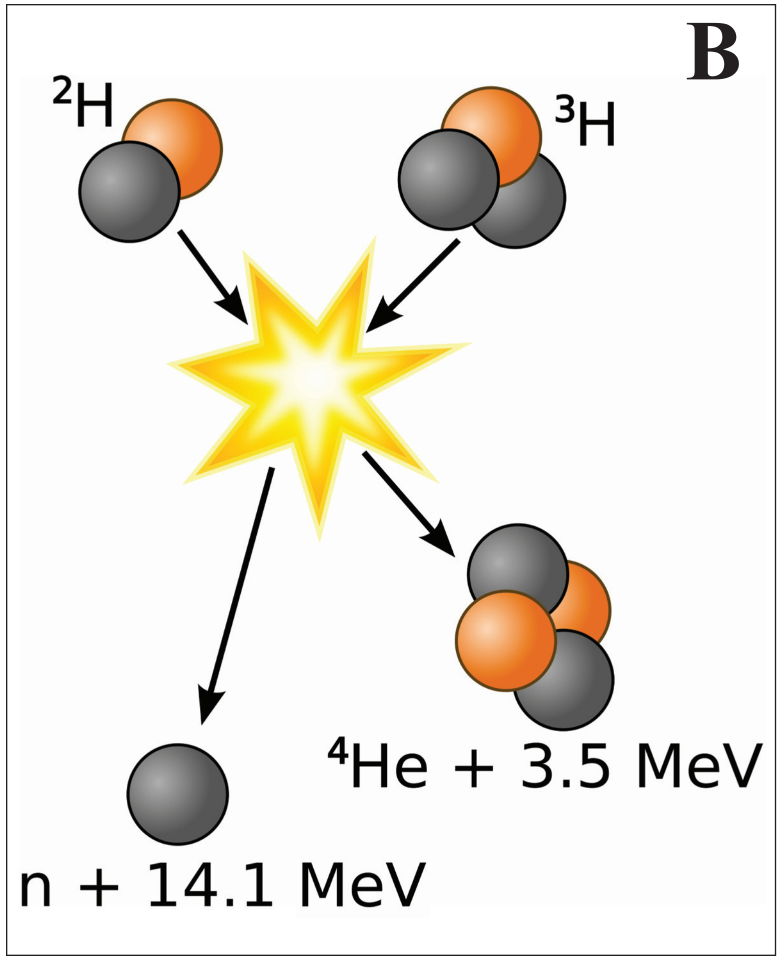


Figure 3A. Nuclear fission reaction showing the capture of a neutron by ^{235}U to produce the short-lived ^{236}U isotope. The ^{236}U rapidly decays into lighter elements producing radiation, more neutrons, and energy (from en.wikipedia.org/wiki/Nuclear_fission). (Note: ^{236}U can also fission into other daughter products, e.g., ^{100}Sr, ^{134}Xe, plus two neutrons.) B. Nuclear fusion reaction showing the fusing of deuterium (^2H) and tritium (^3H) to produce helium, energy, and a neutron. (From en.wikipedia.org/wiki/Nuclear_fusion) (U – uranium; Kr – kypton; Ba – barium; H – hydrogen; He – helium; MeV – mega-electronvolt (one million electronvolts).

(melted tuff), and an envelope of fractured rock (with increased permeability) extended away from the collapse breccia (later called chimney). Johnson et al. (1959) determined that "….. the temperature a few microseconds after detonation was about 1,000,000^{o}K and the pressure 7,000,000 bars (atmospheres)" (p. 1467) and "…. when first formed, the cavity was lined with about four inches of melted rock. …. The cavity stood long enough, 30 sec to 2 min, for much of the fluid rock to flow down the sides and to drip from the roof. At this time the cavity began to collapse and to cool rapidly. … The cavity was filled with broken rock from the collapse, and the caving progressed vertically …" (p. 1465).

The formation of a rubblized cavity (chimney) surrounded by fractured rock was the impetus for several later proposals, including fracture-stimulation for natural gas.

Project Gnome was the first nuclear detonation carried out under the Plowshare program (USDOE, LM, 2009). It consisted of a 3.1-kt nuclear detonation at a depth of 1183 ft in bedded salt in the Permian Salado Formation (Figure 5) in SW/4 NE/4 sec. 34, T. 23 S., R. 30 E.), Eddy County, New Mexico in the northern part of the Delaware Basin. The purpose of the test was multifold: to determine 1) if the molten salt that was produced could be used as a source of geothermal energy and 2) if the radioisotopes that were produced in the salt could be mined; to study 3) neutron physics, 4) certain geophysical characteristics of salt, and 5) the differences between natural earthquakes and nuclear explosions. In addition, small reservoir rock and oil samples were put in containers and placed near the detonation site to determine the effects of the shock wave, high pressures, and radiation on the hydrocarbons (Coffer et al., 1964).

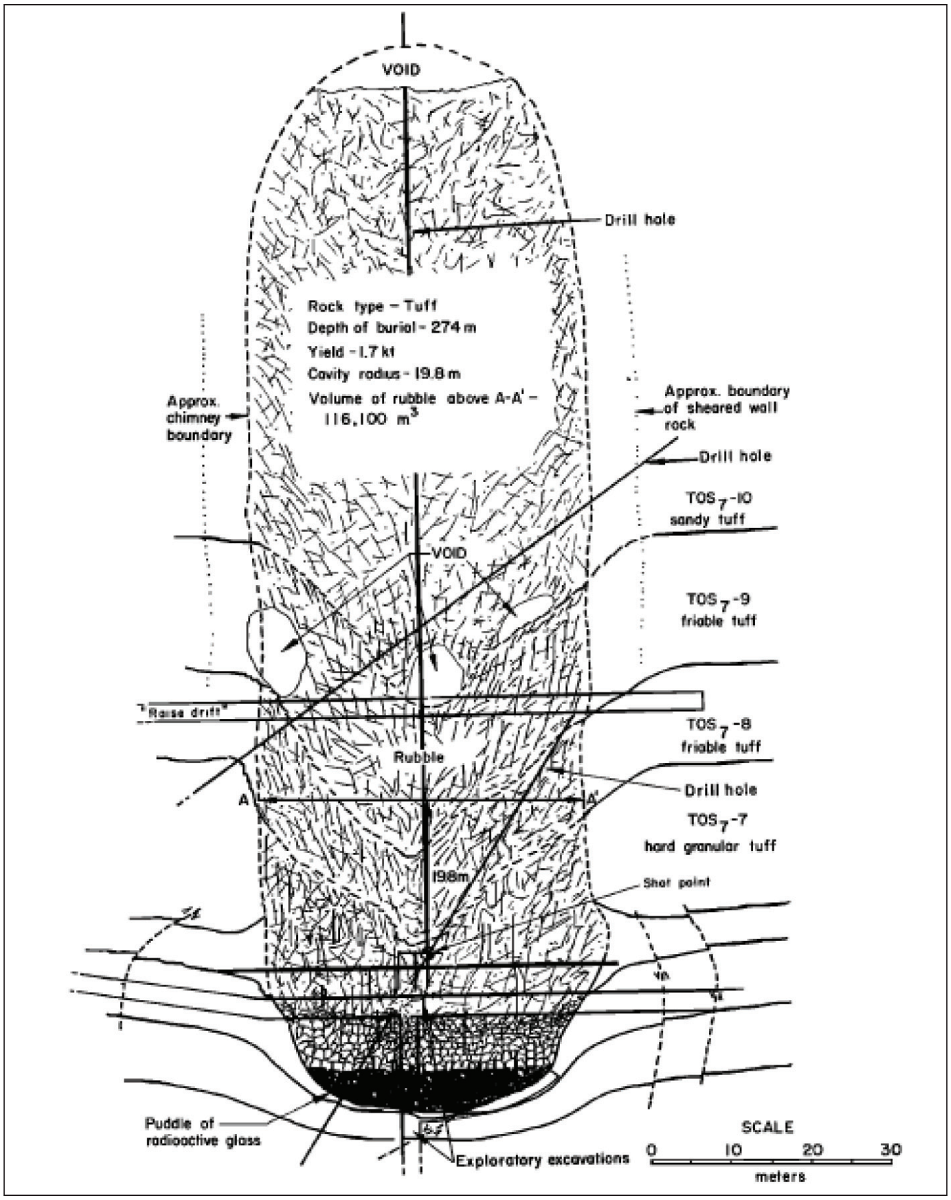


Figure 4. Cross section of the Rainier cavity (chimney) (from Boardman et al., 1964, figure 3).

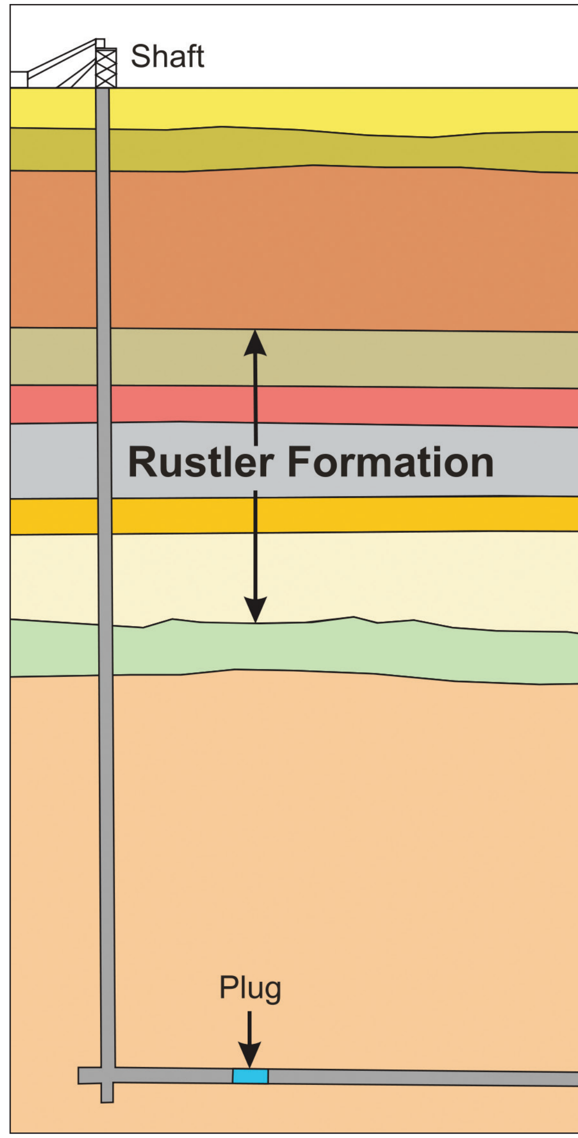
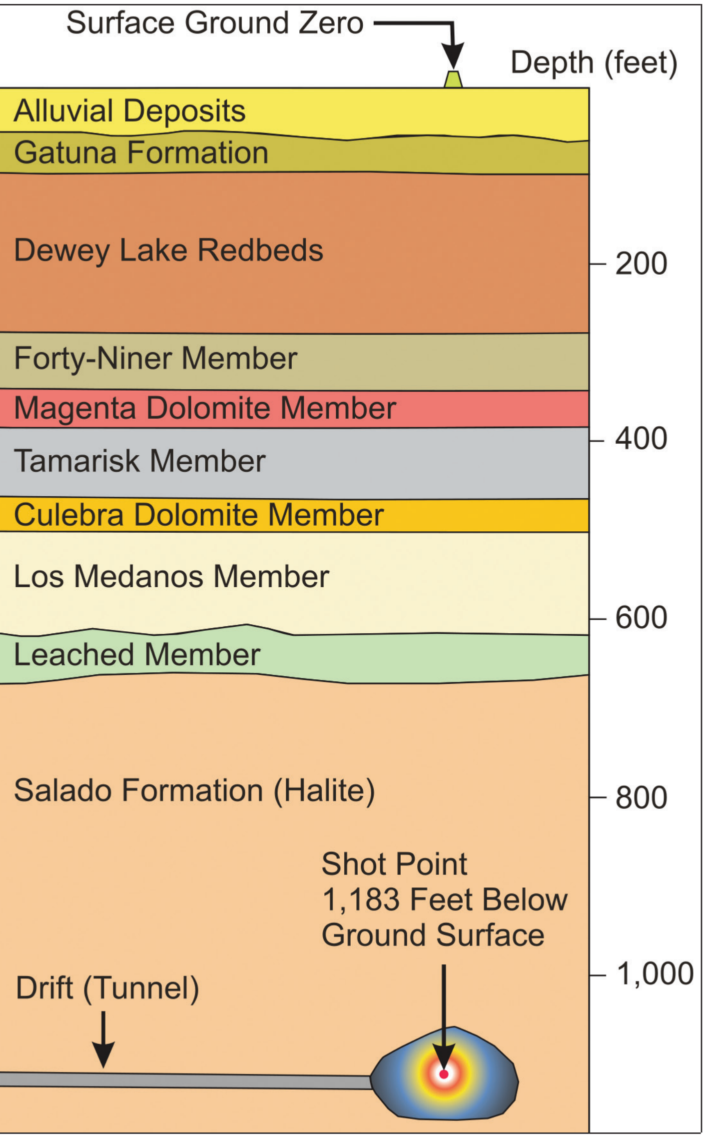


Figure 5. Geologic cross section of the Gnome site (from U.S. DOE Legacy Management Fact Sheet, www.lm.doe.gov/Gnome/Fact_Sheet_-_Gnome-Coach,_New_Mexico.pdf).

The detonation occurred on December 10, 1961 and melted about 2400 tons of rock. In addition to the rubble zone formed by the partial collapse of the roof, a cavity about 150 ft in diameter and 70 ft high was left open (Figures 6A, 6B). The test resulted in an understanding of the details of cavity formation, and radial fracturing and partings along bedding planes resulted in an increase in permeability lateral to and above the shot point (Rawson et al., 1964). Studies of the reservoir samples placed near the shot point showed that carbonates had an increase in porosity and permeability, whereas the sandstone samples had a decrease in permeability and no change in porosity. The shock wave and radiation had little effect on the oil samples. However, the accidental venting of radioactive gas through the access shaft (Figure 5) to the device caused a second nearby test, named Coach, to be cancelled.

The Hard Hat event on February 15, 1962 at the NTS was done as a weapons test, but a number of geological studies were completed on the surrounding rock following the explosion (Short, 1966). The 5.7 kt device was detonated at a depth of 943 ft in granodiorite of the Climax stock and resulted in cavity about 125 ft in diameter that collapsed to produce a chimney 236 ft high (Figures 7A, 7B). Using unoriented cores cut into and around the chimney, Short (1966) studied the bulk density, porosity, sonic velocity, Young's



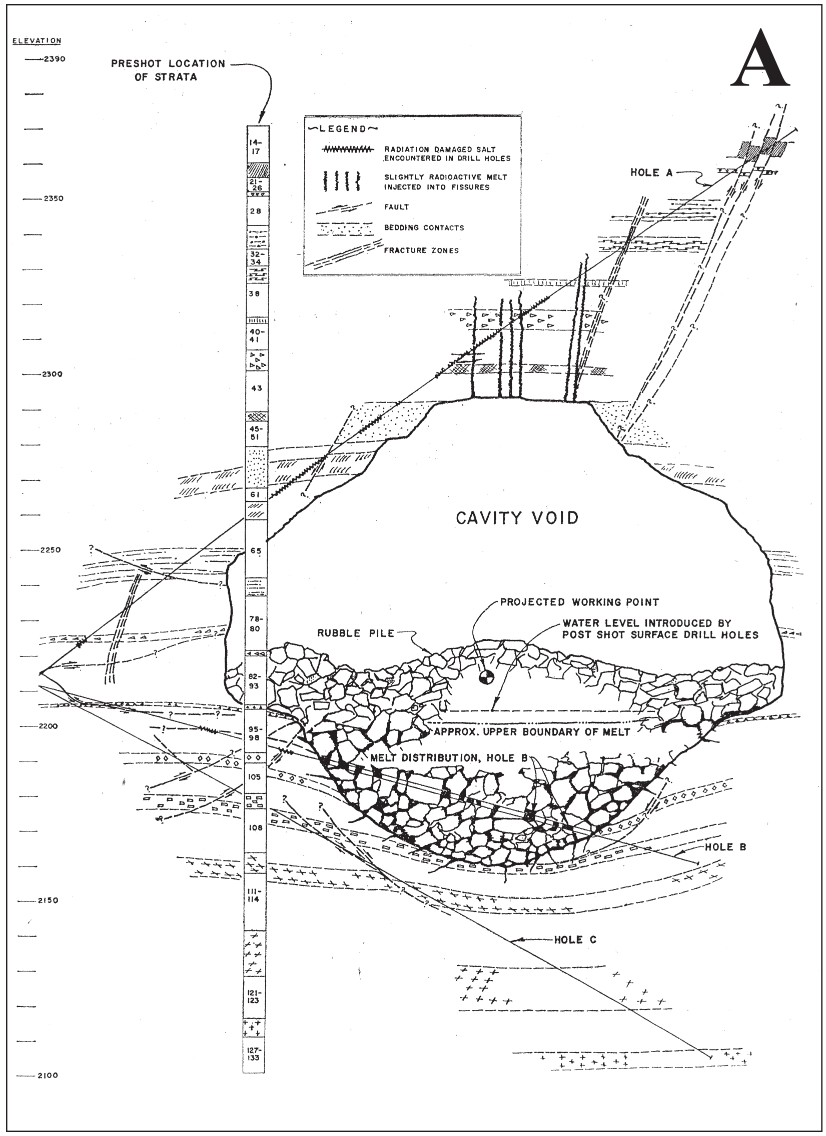
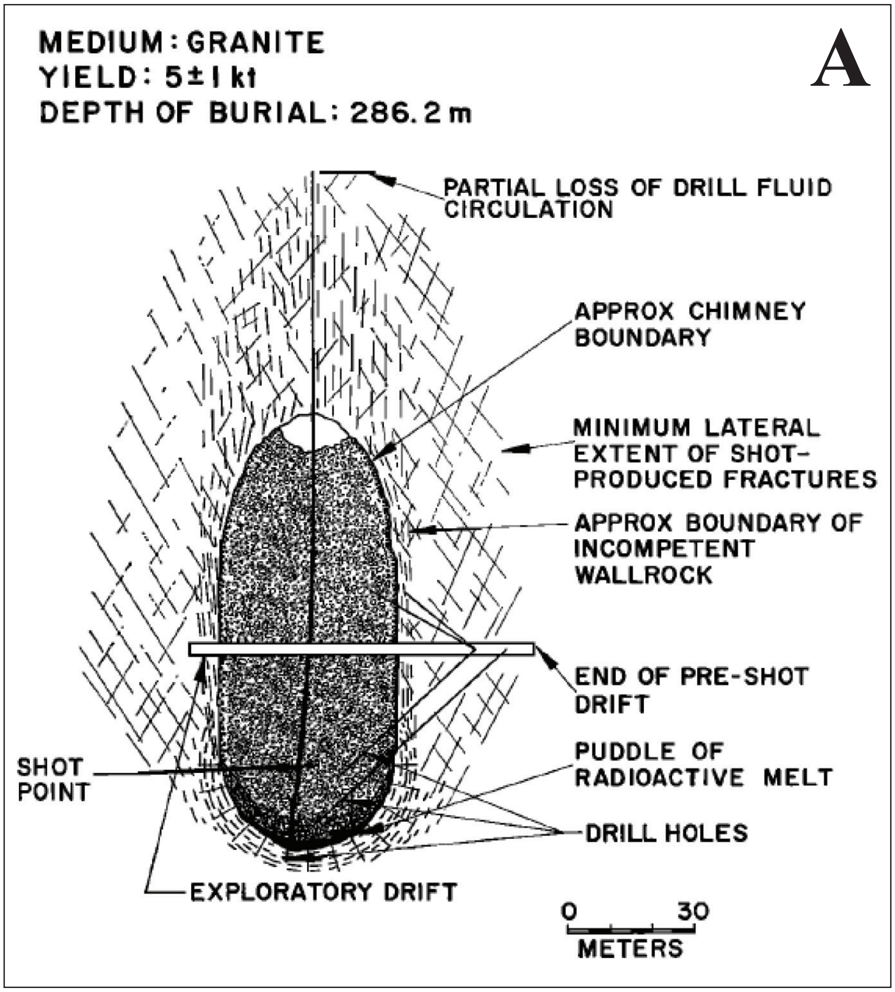


Figure 6. A. Cross section through the Gnome cavity showing location of the shot point (projected working point) and post-shot drill holes drilled from access drift (from Rawson, 1963, figure 3). B. Color image similar to figure 4 of Rawson (1963) showing interior of Gnome explosion-produced cavity. The cavity was entered about five months after the detonation and the radiation level was about 20 mREM/hr (average chest X-ray is 2 mREM).



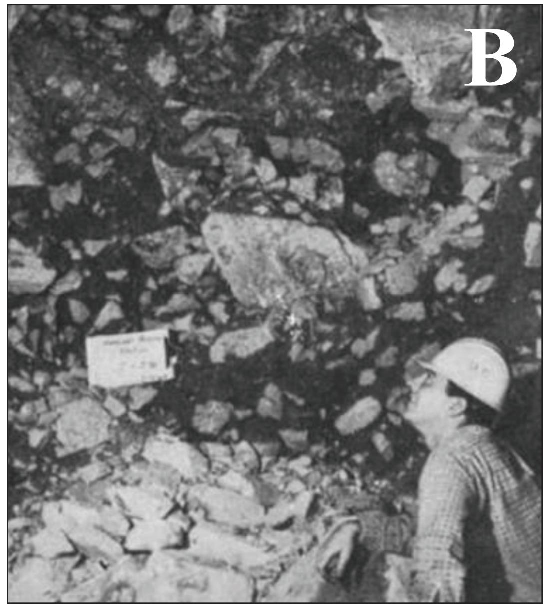


Figure 7. A. Schematic cross section through the Hard Hat chimney and cavity (from Short, 1966, figure 1; also from Boardman et al., 1964, figure 4). B. Brecciated granodiorite in Hard Hat chimney 89 ft above shot point and 10 ft inside chimney (from Boardman et al., 1964, figure 10).

modulus, permeability, crushing strength, and magnetic susceptibility of the granodiorite as a function of distance from the shot point. Short (1966) also defined a "fracture index" (average fracture density per thin section) and showed that the degree of microfracturing increased toward the shot point. Based on the Rainier and Hard Hat tests, Boardman et al. (1964) concluded that detonation-induced fractures extended two to three cavity radii laterally away from, less than 1.5 radii below, and six to eight radii above the device shot point. In addition, they concluded that the four rock mediums (tuff, granite, rock salt, and alluvium) have little effect on cavity size, rather, cavity size is controlled by the 1) yield of the nuclear device, 2) bulk density of rock above the charge, 3) burial depth, and 4) the amount of gas-producing materials (typically, water) near the shot point.

The Sedan test on July 6, 1962 at the NTS was done as part of the Plowshare program to test the effectiveness of nuclear explosions for excavating harbors, canals, passages through mountains, and open-pit mines. Although the test had no bearing on geologic investigations, it was notable for several reasons. Sedan was a thermonuclear device (<30% fission, ~70% fusion) with a 104 kt yield. It produced the largest man-made crater in the U.S. (320 ft deep, 1280 ft in diameter) (Figure 8) and displaced 7.5 million cu yds of alluvium. The radioactive fallout from the blast contaminated more citizens in the U.S. – mostly in eight counties in Iowa – than any other nuclear test. The test produced about 7% of the total amount of radiation that fell on U.S. citizens during all the NTS tests (http://en.wikipedia.org/wiki/Sedan_(nuclear_test)). The Sedan test ended the idea of using nuclear explosions for excavation purposes.

The 12 kt Shoal test on October 26, 1963 was done as part of the Vela Uniform program, the purpose of which was to identify and locate underground nuclear explosions and distinguish them from natural earthquakes. The test was the third outside of the NTS (the first two being Trinity and Gnome) and was located in the Sand Springs Range about 28 mi southeast of Fallon, Nevada in SE/4 SE/4 sec. 34, T. 16 N., R. 32 E. The device was detonated in granite at a depth of about 1211 ft, produced a rubble chimney about 356 ft high,

Figure 8. Sedan crater. Photo courtesy National Nuclear Security Administration / Nevada Field Office, photo number NF-12187 (www.nv.doe.gov/library/photos/photodetails.aspx?ID=799).

and, significantly, did not trigger any subsequent earthquakes despite having been conducted in an area with recent faults (Figure 9).

The 5.3 kt Salmon test on October 22, 1964, was also part of the Vela Uniform program and was done to evaluate seismic signals from nuclear explosions in salt (in this case, the Tatum Salt Dome). It is significant because it and a subsequent test – Sterling – are the only nuclear tests done in the eastern U.S. – both were located in SE/4 SE/4 SE/4 sec. 11, T. 2 N., R. 16 W. about 21 mi southwest of Hattiesburg in Lamar County, Mississippi. The tests were designed to improve the ability to recognize seismic signals from nuclear detonations in a salt dome (Rawson et al., 1967). The result of the explosion was a spherical cavity 114 ft in diameter floored by a puddle of molten salt about 32 ft deep (Figure 10). Microfractures extended radially as far as 300 ft from the edge of the cavity (Rawson et al., 1967). Sterling was a 0.4 kt test conducted on December 3, 1966, in the Salmon cavity and was also designed as a geophysics experiment.

The Handcar test on November 5, 1964 at the NTS was part of the Plowshare program and was conducted to determine the effects of an underground nuclear explosion on carbonate rocks (dolomite) and to study the effect of explosion-produced CO_2 on the formation of the cavity. The 12 kt device was detonated at a depth of 1332 ft and produced a chimney 138 ft in diameter and 233 ft high (Figure 11). Although the size of the cavity was different than predicted, Werth (1962) concluded that the thermal decomposition of the dolomite and produced CO_2 had little effect on the formation of the chimney and that the single most important factor control-

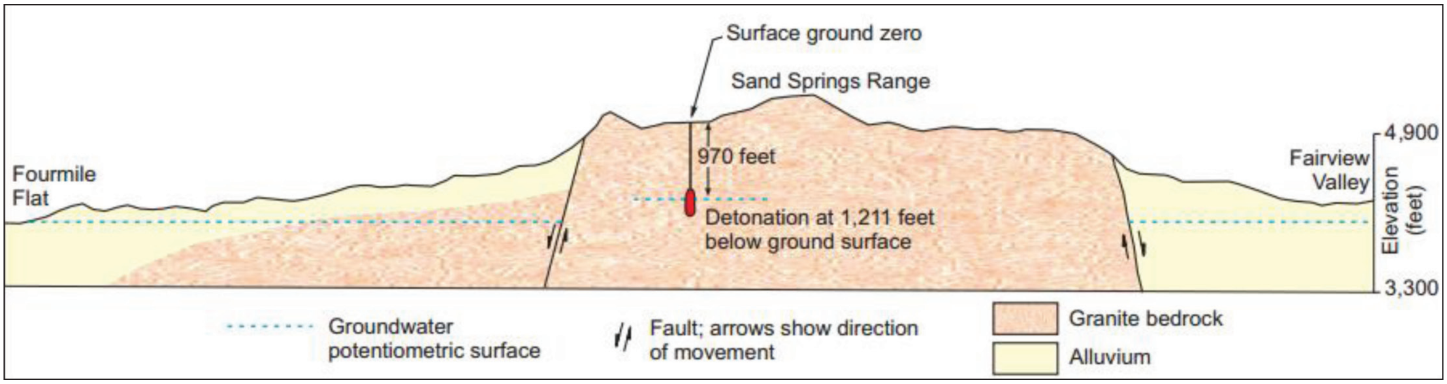


Figure 9. Schematic cross section of Sand Springs Range and Shoal nuclear test site (from U.S. DOE Legacy Management Fact Sheet, www.lm.doe.gov/Shoal/fact_sheet.pdf).

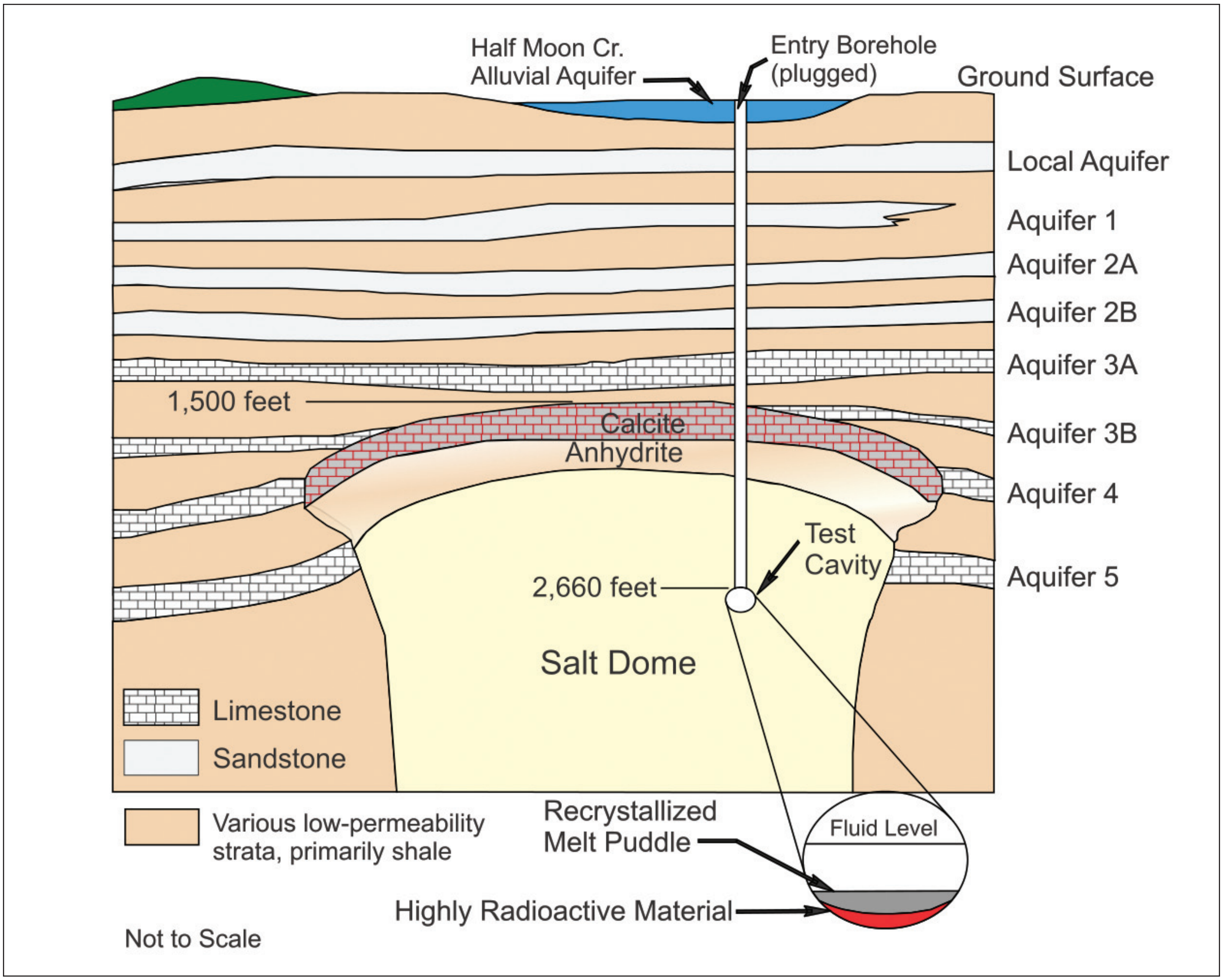


Figure 10. Schematic cross section through Tatum Salt Dome and Salmon nuclear test site (from U.S. DOE Legacy Management Fact Sheet, www.lm.doe.gov/Salmon/Fact_Sheet_-_Salmon.pdf).

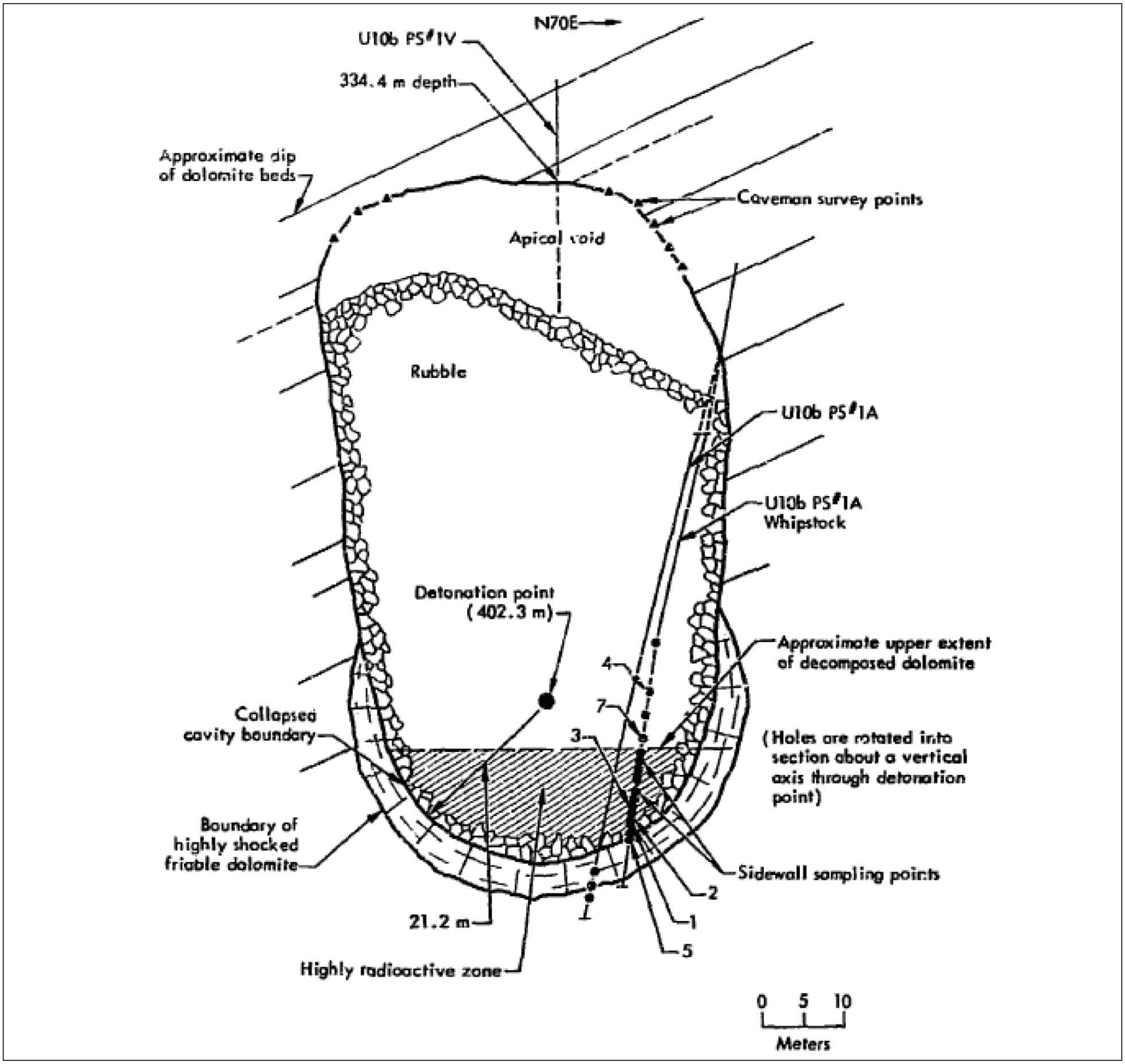


Figure 11. Cross section through the Handcar chimney one year after detonation (from Werth, 1962, figure 30).

ling cavity radius was the water content of the host rock. Werth (1962) noted, however, that the dolomite in which the detonation occurred was highly fractured and that this may have reduced the effect of the CO_2.

NUCLEAR NATURAL-GAS STIMULATION TESTS

Justification

Three factors drove the effort to develop nuclear-fracturing technology: 1) the forecast that the demand for natural gas would outstrip the nation's supply; 2) the recognition that several of the Laramide basins in the western U.S. contained enormous reserves in porous, but low-permeability, reservoirs that were uneconomic using then-current completion techniques; and

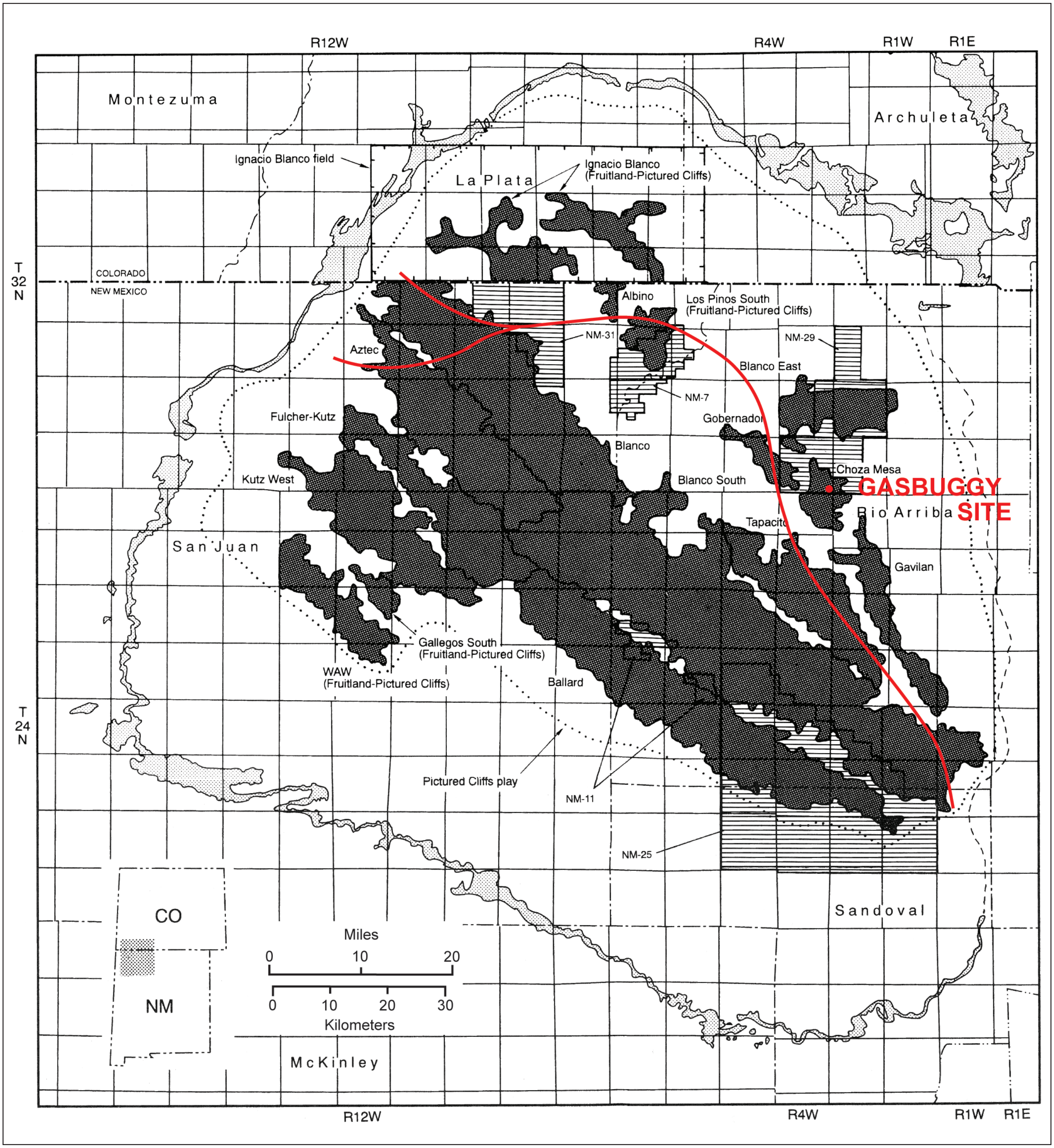


Figure 12. Map of San Juan Basin showing distribution of Pictured Cliffs reservoirs (dark pattern), Federal Energy Regulatory Commission (FERC) – designated Pictured Cliffs tight-gas-sand areas (lined areas), axis of basin (red line), and location of Gasbuggy site (modified from Whitehead, 1993b).

3) the availability of nuclear expertise during a period of expected reduced numbers of weapons tests. Rubin et al. (1972) described the predicted gap between supply and demand for natural gas in the U.S. and the shortages that began to appear in the late 1960s. The shortages were the result of price controls by the Federal Power Commission and were manifested by part-time or off-peak takes by or curtailments of interruptible gas customers and the refusal by distributors to accept new customers. The price controls benefited consumers, especially those not requiring interstate gas transmission, but discouraged producers. The price drop resulted in decreased production which resulted in shortages.

Haun et al. (1970) suggested 100 to 200 tcf of discoverable gas was present in the Rocky Mountain basins with about 90% of that being in the Green River, Uinta, and Piceance Basins. They also noted that Robert Johansen (U.S. Bureau of Mines) reported that 317 tcf gas could be produced using nuclear stimulation in the San Juan, Green River, Uinta, and Piceance Basins (Western Oil Reporter, January 1970, p. 37). Clearly the gas was there; all geologists and engineers had to do was figure out a way to produce it.

Gasbuggy

Geology

The Gasbuggy site is located in the San Juan Basin in northwestern New Mexico (Figure 12). The San Juan Basin is a prolific hydrocarbon-producing basin that covers about 7500 sq mi, mostly in San Juan, Sandoval, and Rio Arriba Counties in New Mexico, and La Plata and Archuleta Counties in Colorado. It is about 100 mi in diameter and roughly circular in plan. The basin is structurally asymmetric – strata on the northwest and northeast sides dip steeply into the basin and those on the southern side dip gently. Over 14,000 ft of Cambrian through Tertiary rocks are present in the deepest part of the basin, and the Upper Cretaceous section (Gasbuggy test) is over 6000 ft thick (Fassett and Hinds, 1971). The Upper Cretaceous strata consist of interfingering marine and nonmarine strata that represent repeated transgressions and regressions of the Western Interior Seaway across the basin.

The San Juan Basin produces primarily gas from six reservoirs; all but one (Pennsylvanian) are in Upper Cretaceous strata and include (oldest to youngest) 1) Dakota, Dakota/Morrison; 2) Gallup, Tocito, fractured Mancos; 3) Mesaverde; 4) Pictured Cliffs (Gasbuggy test); and 5) Fruitland (Whitehead, 1993a). As of 2009, the Pictured Cliffs Sandstone had produced about 4.5 TCF gas or about 10% of the total amount of gas in the basin (Fassett, 2010). Pictured Cliffs production fairways are oriented northwest-southeast in the center of the basin (Figure 12) and probably reflect sandstone thicks produced by sea-level stillstands followed by sea-level rise (Fassett and Hinds, 1971, fig. 5).

Cumella (1981) (cited in Hoppe, 1992) divided the Pictured Cliffs in the San Juan Basin into three general areas, including a southwest zone of permeable water-saturated sandstone, a central zone (producing fairway) in which production was from porous and permeable rocks enhanced by fractures, and a northeast zone of low permeabilities in which production was dependent on fractures. The low porosities and permeabilities in the northeast are caused by "deformation of ductile framework grains (sedimentary and volcanic rock fragments) and/or the precipitation of authigenic clays (illite and/or mixed-layer illite-smectite) and dolomite in the pore system" (Hoppe, 1992, p. 365).

The stratigraphy and petrology of the Pictured Cliffs Sandstone is well known. The Lewis Shale underlies the Pictured Cliffs (Figure 13); the contact is gradational and the two formations interfinger. The nonmarine Fruitland Formation overlies the Pictured Cliffs and it, like the Lewis Shale, grades into and interfingers with

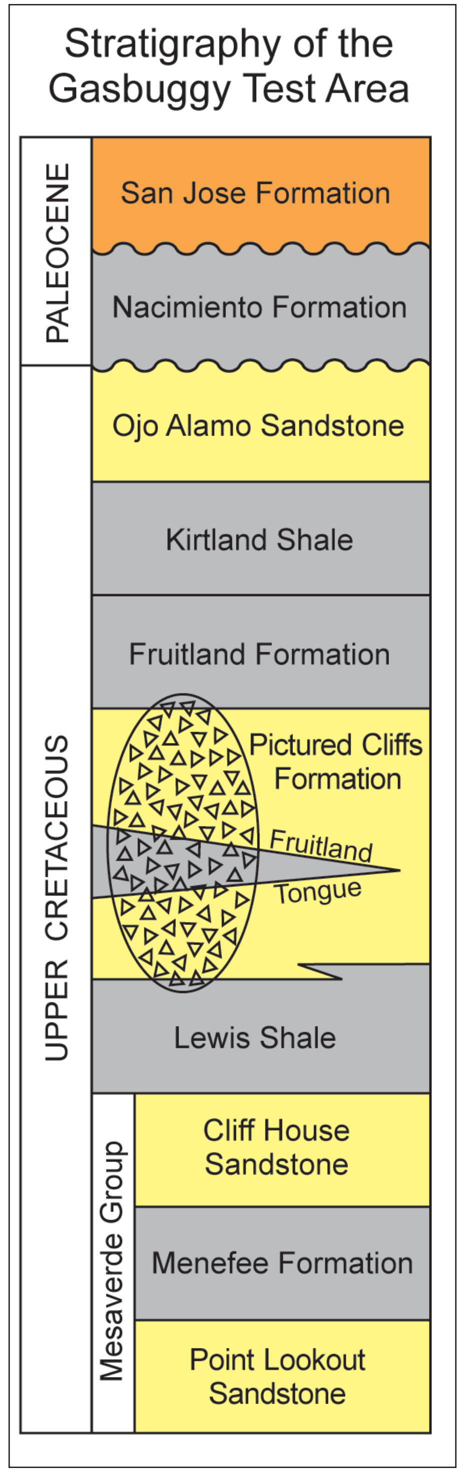


Figure 13. Stratigraphy of the Gasbuggy site.

the Pictured Cliffs. The Lewis is a marine siltstone and shale, the Pictured Cliffs is a siltstone and sandstone deposited in a wave-dominated shoreline environment, and the Fruitland is a coastal plain deposit that includes fluvial, overbank, floodplain, swamp, and tidal deposits (Hoppe, 1992). The sequence represents the final withdrawal of the Western Interior Seaway marked by the upward change from marine shale to shoreline sandstones to coastal-plain deposits. A core through the Pictured Cliffs Sandstone about 160 ft north of the Gasbuggy shothole showed the unit to consist of two parts – a lower part 137 ft thick consisting of fine- to very fine grained sandstone with thin shale interbeds and a very similar upper part 128 ft thick. The two parts are separated by a 17-ft-thick tongue of the Fruitland Formation (Fassett, 1968).

The Gasbuggy site is located in the NW/4 SW/4 sec. 36, T. 29 N., R. 4 W., in Rio Arriba County, New Mexico. The site is in the Choza Mesa Gas Field which was discovered by the El Paso Natural Gas No. 2 San Juan 29-4 well in 1953 (Brown, 1978). The field produces gas only from the Pictured Cliffs Sandstone at about 3950 ft. Early completion consisted drilling to the top of the Picture Cliffs, setting casing, having a cable-tool rig drill through the formation, and fracturing the open hole with solidified nitroglycerine from TD to just below the casing (Brown, 1978). Another method of well completion was open-hole sand-water fracturing. Beginning in the mid-1950s cased-hole hydraulic fracturing became the norm.

The Choza Mesa Field is northeast of the main producing fairway of the Pictured Cliffs Sandstone east of the axis of the San Juan Basin and is within the FERC-designated tight-gas-sand area (Whitehead, 1993b). Brown (1978) showed a permeability range of 0 to 0.84 md (average 0.15 md) but noted that production is largely from fractures, Hoppe (1992) showed permeabilities ranging from <0.01 to 0.77 md, and Whitehead (1993b) showed an average permeability of 0.008 md. Ward et al. (1966) calculated in-place reserves of 33 MMcf/acre or 5280 MMcf/160-acre and determined that only 10% of in-place gas was being recovered by existing wells that were hydraulically fractured. They predicted 67% ultimate recovery of in-place gas at a 160-acre spacing following nuclear fracturing.

Two pre-shot wells, GB-1 and GB-2, were drilled about 175 ft northwest of, and 300 ft east of, respectively, the emplacement well (GB-E) to better characterize the Pictured Cliffs Sandstone reservoir (Ward and Lemon, 1968). Both were cored and logged, and GB-1 was flow-tested. (The production from GB-2 was so low that only open-flow tests were conducted on it.) The results showed that production was entirely from fractures.

Detonation

The Gasbuggy test consisted of a single 29-kt fusion device (Figure 14) that was detonated at 12:30 p.m. MST on December 10, 1967 at a depth of 4240 ft, approximately 42 ft below the base of the Pictured Cliffs Sandstone in the Lewis Shale. The overall objective of the test was to determine the extent to which a low-permeability gas-bearing sandstone could be stimulated using a nuclear explosive (Rawson et al., 1968) and specifically the chimney configuration, void volume and permeability and, perhaps most importantly, the permeability of the fractured reservoir rock outside the chimney (Lemon and Patel, 1972). Other objectives of the test were to: 1) determine the extent and character of the shock-wave effects; 2) measure any change in the productivity of nearby existing wells; 3) measure the radioactivity of the produced gas; 4) further study the thermodynamics of the fission reaction, and 5) to further study the seismic effects of a nuclear detonation outside the NTS and western Pacific (Rawson et al., 1968, Ward et al., 1966).

Gasbuggy was a joint experiment between the AEC, the U.S. Bureau of Mines (Department of the Interior), and El Paso Natural Gas Company, with technical assistance by Lawrence Radiation Laboratory. Studies of the area prior to the shot included characterizing the geology and production history of eight gas wells in the Choza Mesa Field and within about a mile of the site and drilling, coring (Pictured Cliffs Sandstone), logging, and production testing two test wells – GB-1 located about 170 ft north-northwest of the emplacement well (GB-E) and GB-2, 280 ft east of GB-E.

The Gasbuggy shot generated a magnitude 4.5 +/- 0.3 to 5.2 earthquake (Corbishley, 1970; Reagor et al., 1968), but very little surface disturbance was evident at ground zero soon after the shot or at the nearby gas-well surface facilities. Two dams 24 mi west and 26 mi east of the site were undamaged; buildings, tunnels, and mines in the area were also undamaged (Holzer, 1968). There were three complaints of structural damage, but the damage in only one may have been caused by Gasbuggy (Holzer, 1970). About eight hours after the shot small amounts of radioactive ^{133}Xe and ^{85}Kr were detected at the surface at the GB-E wellhead that apparently had migrated up a cable. The wellhead was sealed and the release of radioactive gasses stopped (Holzer, 1968).

Results

The Gasbuggy nuclear detonation produced a rubble-filled chimney about 333 ft high and 160 ft in diameter; the upper part consisted of sagged strata that was brecciated and contained rubble-filled voids (Figure 15). On December 13, 1967, three days after the detonation, GB-E was re-entered (GB-ER). The drilling encountered the top of the chimney at 3890 ft and a void at 3907 ft (Ward and Lemon, 1968). Steel at the bottom of the void prevented drilling deeper so the hole was logged and flow-tested. GB-2 was re-entered (GB-

2R) in June, 1968, encountered damaged casing at 3691 ft, was sidetracked (GB-2RS), and drilled to 4600 ft. Hole problems prevented testing and the hole was logged to 4224 ft. A third post-shot hole, GB-3, located about 250 ft northwest of GB-E, was spudded in August 1969 and drilled to 4800 ft. The hole was cored, logged, and production-tested.

Based on the production tests completed in GB-ER, Atkinson et al. (1970) estimated that GB-ER produced at six to seven times the rate of the nearby hydraulically fractured pre-shot field wells and would produce 900 mmcf gas in 20 yrs, or about 19% of the original gas-in-place over 160 ac. This was about five times the EUR of a conventionally completed well in the field. Production tests of GB-2RS suggested that there was some increase in productivity due to fracturing as a result of the detonation, but the increase was similar to that of hydraulically fracturing a well (Ward and Lemon, 1968). In addition, the fractures in GB-2RS did not appear to be connected to the chimney. Tests, cores, and logs from GB-3 showed that it was similar to pre-shot GB-1 but more fractured (Atkinson et al., 1970). The well produced less gas than predicted and showed an absence of fracture communication with the chimney.

The shot-produced fracture network in the Pictured Cliffs Sandstone at Gasbuggy extended about 220 ft from the edge of the chimney, or about 2.75 times the chimney radius (here, 80 ft) (Lemon and Patel, 1972). They also suggested the pre-shot formation permeability was a key factor in the ultimate recovery from nuclear-stimulated wells.

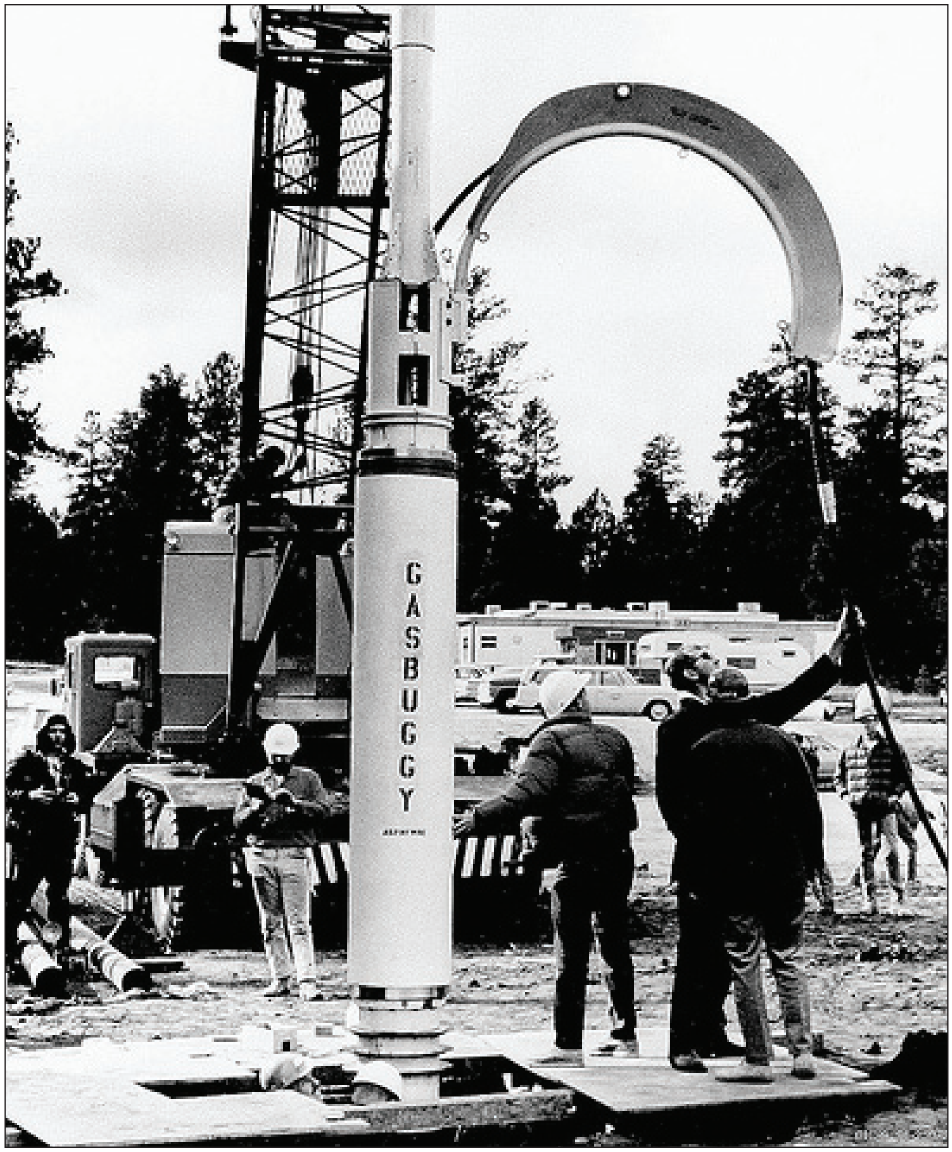


Figure 14. Gasbuggy nuclear device (13 ft long, 18 in. in diameter) being lowered into emplacement hole GB-E (www.lanl.gov/newsroom/photo/history.php; history, gasbuggy device).

Rulison

Geology

The Rulison site is located in the Piceance Basin in northwestern Colorado about seven miles southeast of the town of Parachute (Figure 16). The Piceance Basin is a major hydrocarbon-producing Laramide basin that covers about 4000 sq mi mostly in Mesa, Garfield, and Rio Blanco Counties. It is about 100 mi long in a northwest-southeast direction and 40 to 50 mi wide northeast-southwest. It is asymmetric with relatively gently dipping west and southwest flanks and a steeply dipping east flank known as the Grand Hogback. In its deepest part, the basin contains 27,000 ft of Cambrian through Eocene sedimentary rocks (Tremain, 1993a), including over 11,000 ft of Upper Cretaceous strata (Rulison test).

The Piceance Basin is particularly well known for its Eocene oil shale reserves which have been extensively studied but are, as yet, uneconomic to produce. (As briefly noted above, one of the early Plowshare ideas was to use nuclear explosives to retort, *in situ*, the oil shales. This idea was never tested. In addition, as discussed below, there was concern that the

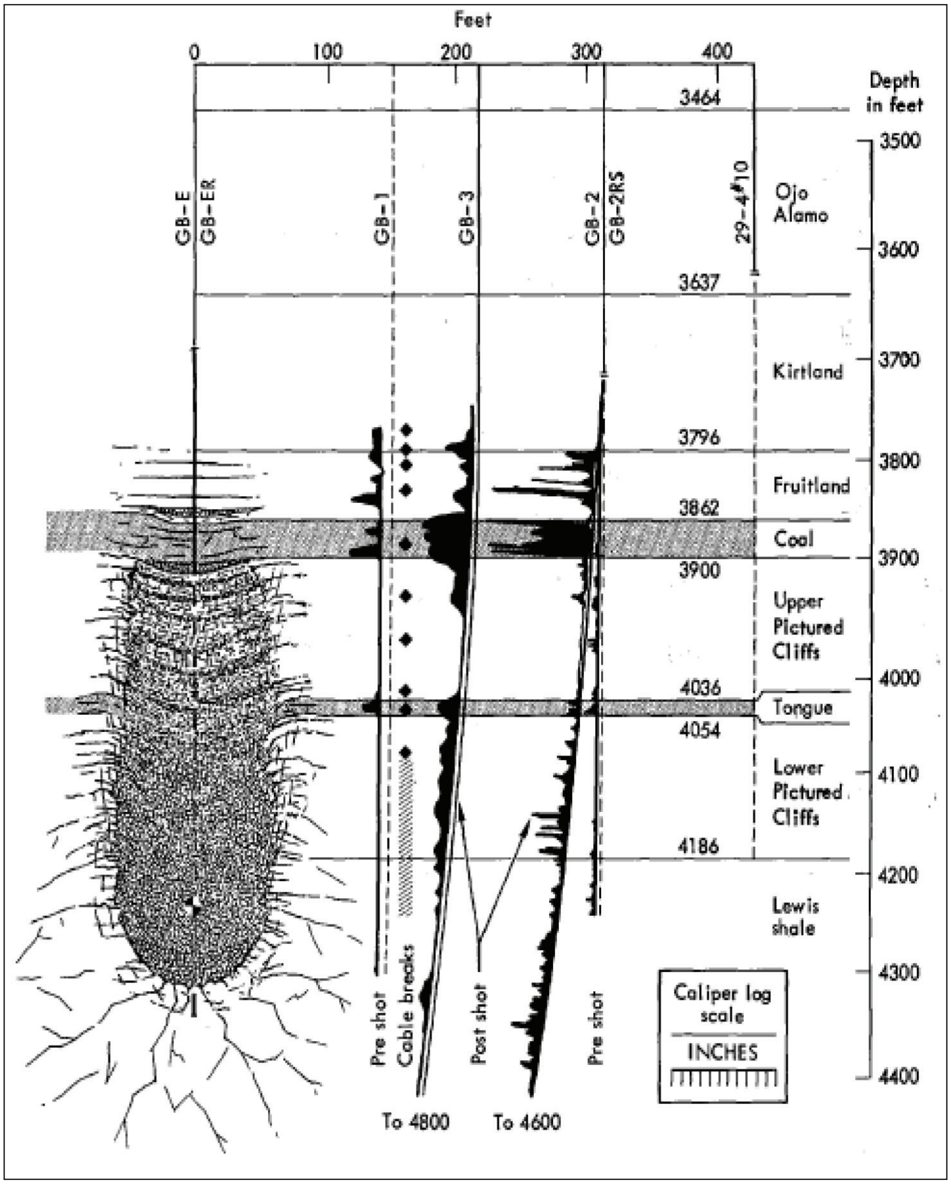


Figure 15. Schematic cross section through the Gasbuggy chimney showing rubble-filled cavity and brecciated and sagged strata at top. Caliper logs of pre- (GB-1 and GB-2) and post-shot (GB-2RS and GB-3) holes give indication of extent of fracturing (from Holzer, 1970, figure 3).

Rio Blanco test would negatively impact on-going oil-shale exploration and development efforts in the basin. It didn't.) Gas is produced from six units within the basin – Weber Sandstone (Pennsylvanian – Permian), Entrada Sandstone (Jurassic), Dakota Group (Cretaceous), sandstones in the Mancos Shale (Cretaceous), Mesaverde Group (Cretaceous), and Wasatch Formation (Paleogene). The principal unit of interest in the Rulison test was the Mesaverde Group, that, as of 1990, had produced about 188 bcf gas or about 8% of the total amount produced in the basin (Tremain, 1993b). Most of the Mesaverde gas fields are located in the southern part of the Piceance Basin (Figure 16); some are located on structural highs and others are deep basin-centered plays (Johnson, 1989). Many studies have concluded that natural fractures are critical for production.

The Mesaverde Group throughout most of the Piceance Basin consists of two units – the Iles Formation below and Williams Fork Formation above (Figure 17). Some authors consider the overlying Ohio Creek Formation to be part of the Mesaverde, but its distinguishing feature – white kaolinitic clays – are a weathering feature. The base of the Mesaverde is also controversial. Hemborg (2000, fig. 2) includes the Castlegate Sandstone as the basal unit of the Mesaverde, whereas Johnson (1989) includes the Castlegate within the underlying Mancos Shale. Regardless of nomenclature, the Mancos (marine) to upper Mesaverde (fluvial) sequence represents the withdrawal of the Late Cretaceous Western Interior Seaway, and individual units in the top of the Mancos and lower part of the Mesaverde represent lower-order transgressions and regressions within the overall withdrawal. Sandstones in the top of the Mancos were deposited in a shelf and/or shoreline environment; the Iles Formation consists of shelf, delta-front, barrier-island, bay-lagoon, and strand-plain deposits; the lower Williams Fork consists of delta-front, distributary-channel, strand-plain, lagoon, and swamp deposits; and the upper Williams Fork consists of fluvial, floodplain, and swamp deposits (Hemborg, 2000).

The Rulison site is located in NE/4 SW/4 sec. 25, T. 7 S., R. 95 W. in Garfield County, Colorado. The site is near the Rulison Gas Field (on some maps, the Parachute Gas Field) which was discovered by the Southern Union No. 1 Juhan-Fee well in 1958, although gas was known in the area since 1944 (Martinez and Duey, 1982). The field produces from the Mesaverde at about 5500 ft to 7700 ft and from the overlying Wasatch Formation, which produces gas at about 1500 ft to 2300 ft. The Rulison Field is one of four gas fields (including the Grand Valley, Parachute, and Mamm Creek Fields) that form an east-west fairway just north of the Mesa – Garfield County line and generally along the Colorado River valley (Hemborg, 2000);

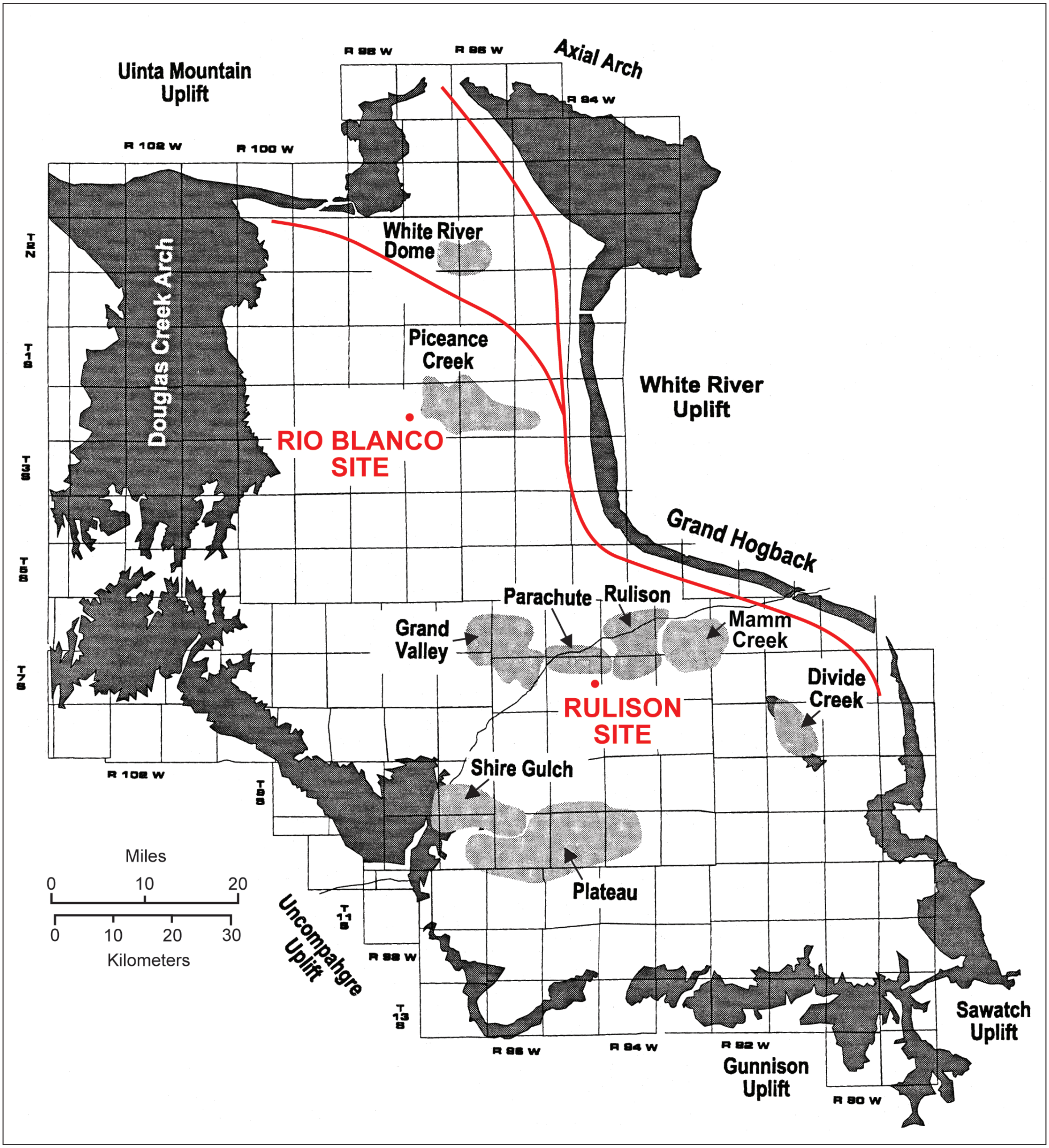


Figure 16. Map of Piceance Basin showing major Mesaverde Group gas fields, location of the Rulison and Rio Blanco sites, and axis of basin (red lines) (modified from Hoak and Klawitter, 1997, figure 1).

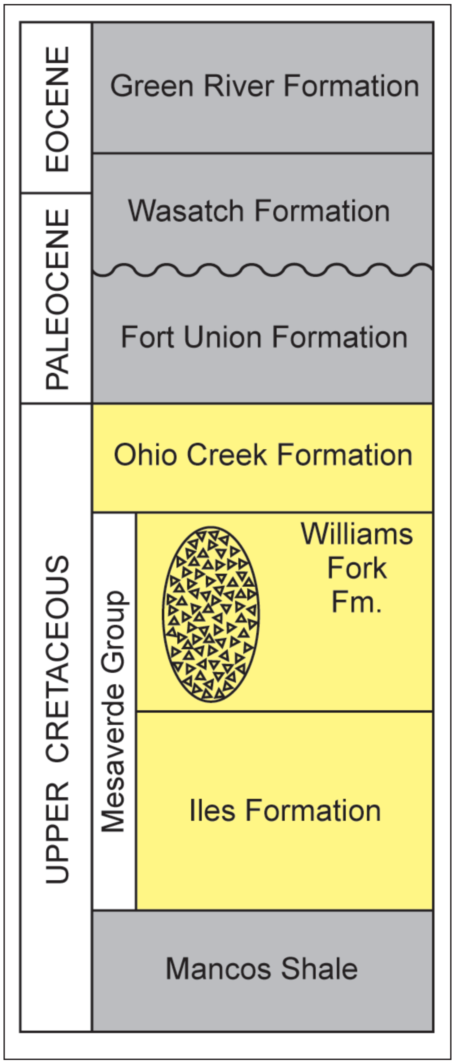


Figure 17. Stratigraphy of the Rulison site.

this fairway coincides with an area in which the upper one-third of the Williams Fork Formation is water-bearing (Tremain, 1993b, fig. PC-2.5).

The Rulison Field is within the FERC-designated tight Mesaverde gas area (Tremain, 1993b). Reservoir pemeabilities are extremely low; conventionally measured permeabilities in cores from three wells located about six miles northeast of the Rulison site (DOE MWX wells in NW/4 sec. 34, T. 6 S., R. 94 W.) range from 0.1 to 1.0 md in the fluvial part of the Mesaverde (Pitman et al., 1989), although these values would probably be lower at reservoir conditions. Martinez and Duey

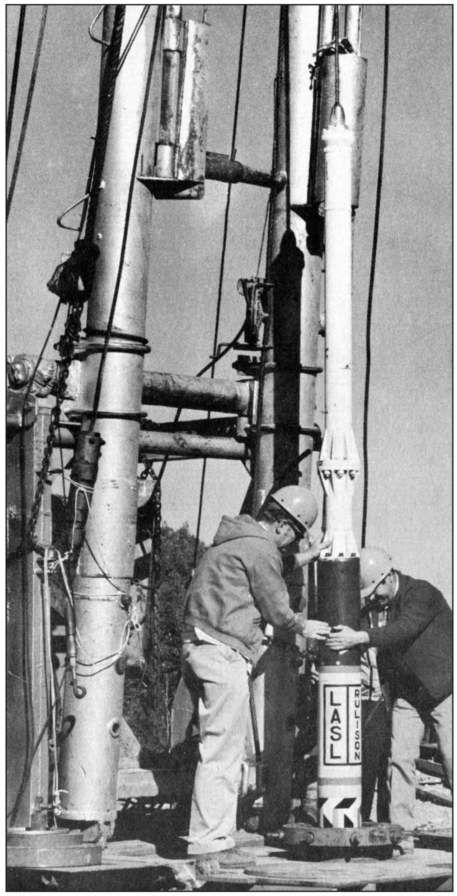


Figure 18. Rulison nuclear device being lowered into emplacement hole R-E (photo by Kelly Michals from https://www.flickr.com/photos/rocbolt/8930807723/).

(1982) gave an average permeability for the Mesaverde in the Rulison Field of 0.054 md based on drawdown tests and Coffer et al. (1970) reported 0.5 md. The permeability of the Mesaverde from a core from the R-EX well immediately adjacent to the emplacement well for the Rulison test was 0.11 md (Coffer et al., 1970). The extremely low permeabilities are caused by the pore spaces being filled with authigenic quartz, feldspar, calcite, dolomite, illite, mixed layer illite-smectite, kaolinite, and iron-rich chlorite (Johnson, 1989).

At reservoir conditions, the Mesaverde Group in the Rulison Field is more permeable to water than gas, and the generation of gas in the lower part of the Mesaverde and the underlying Mancos has driven the water updip, essentially forming a "seal." Natural fractures are necessary for production from the Mesaverde, and modern wells are both left unstimulated and hydraulically fractured.

Detonation

The Rulison test consisted of a 43-kt nuclear detonation at a depth of 8426 ft in the Mesaverde Group. The shot occurred at 3:00 p.m. MDT on September 10, 1969. The device was 9 in. in diameter, 15 ft long, and weighed 1200 lbs (Coffer et al., 1970) (Figure 18) . The primary objective of the test, like that of Gasbuggy, was to determine the potential for fracture-stimulating low-permeability gas-bearing sandstones, in this case, sandstones in the Mesaverde Group (and, in particular, the Mesaverde in the Rulison Field), the Wasatch and Ft. Union Formations, and the Lewis Shale (Reynolds et al., 1970). Secondary objectives included: 1) measuring the effective permeability of the fractured zone outside the chimney; 2) determining how to minimize the radioactive contamination of the natural gas; 3) characterizing the chimney and surrounding fractured zone; and 4) measuring the seismic effects of the detonation (AEC, 1973a).

The test was a joint effort of the AEC, Austral Oil Company, CER Geonuclear Corporation, and the U.S. Bureau of Mines (Department of the Interior), with technical assistance provided by Los Alamos Scientific Laboratory. Based on studies of nine original wells in the field, including two drilled by Austral for the feasibility study, the Mesaverde was shown to contain 90 to 125 bcf gas-in-place/640 ac and that the Rulison Field contained 9 to 12 tcf gas-in-place that was not economically feasible to produce using hydraulic fracturing (Reynolds et al., 1970; Coffer et al., 1970). An exploratory well (R-EX) near the site was spudded on November 9, 1967, TD'd at 8516 ft, and completed on May 6, 1968. The Mesaverde in the well

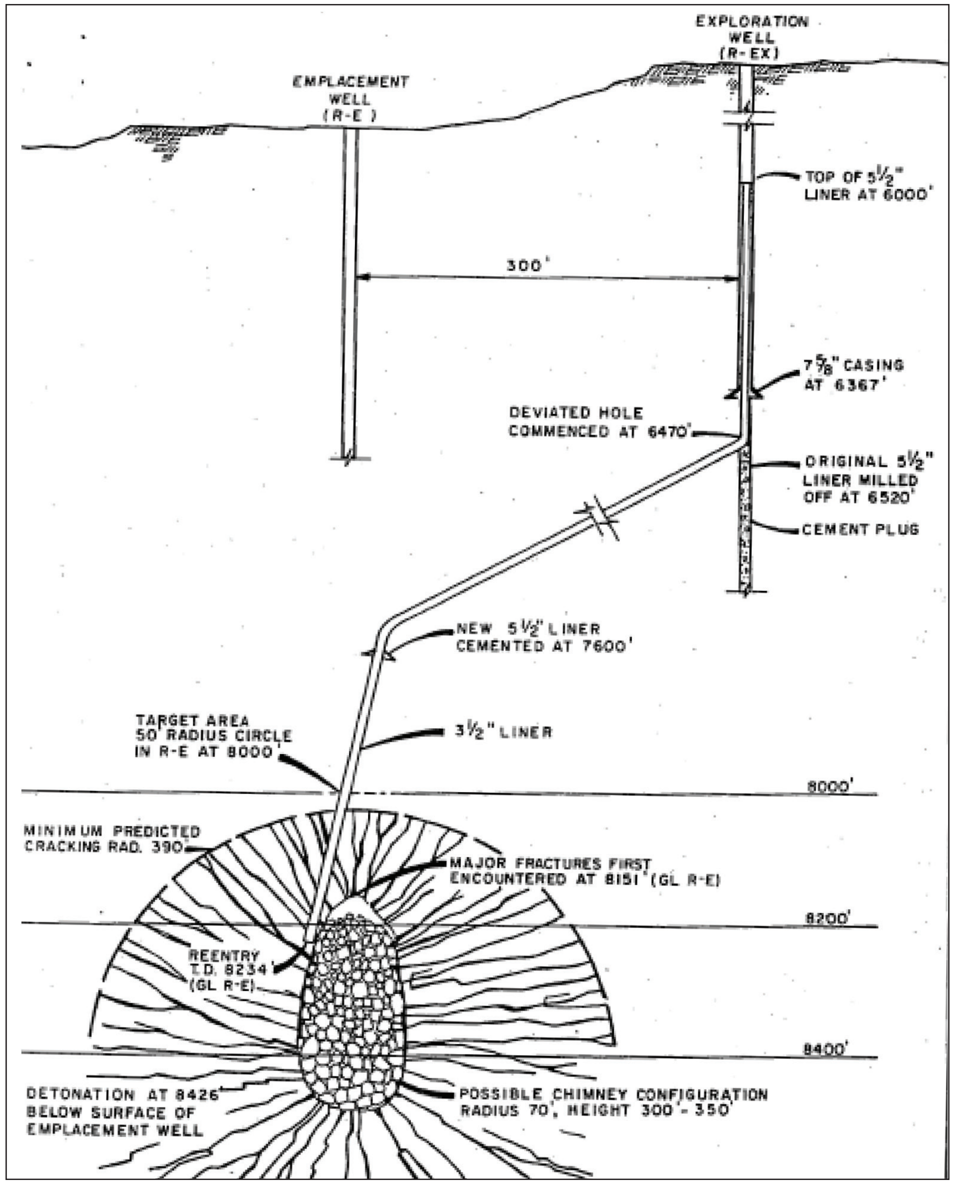


Figure 19. Sketch diagram of Rulison chimney, surrounding fracture zone, and holes R-E, R-EX, and the R-EX redrill (from AEC, 1973a, figure 6).

was cored, logged, production-tested, and given a small-volume hydraulic fracture to determine the reservoir properties and production characteristics. The emplacement hole (R-E) was located 311 ft west-northwest of R-EX and was spudded on September 29, 1968. It TD'd at 8701 ft on January 18, 1969 and was completed on January 30. The well was cored from 8400 to 8460 ft and was logged. An original detonation date of May 22 was postponed to September 4 due to the need for additional safety studies. The device was lowered into R-E on August 15, and the first of three lawsuits was filed on August 22 to stop the test. All three lawsuits were denied by the court, and the test occurred after a slight delay (AEC, 1973a).

Beginning 4.8 secs after the detonation and continuing for about 150 sec afterwards, geophones near ground zero detected subsurface signals consistent with collapse into the shot cavity (Coffer et al., 1970). Some noise continued for 9 hrs. The shot caused a 5.4 magnitude earthquake (Corbishley, 1970) and sixteen aftershocks of magnitude <1 were recorded less than a mile from ground zero in the first 43 mins after the shot. Several hundred claims for relatively minor structural damage were filed as a result of the detonation (AEC, 1973a). No radioactive gas was accidently released following the test.

Results

The Rulison nuclear detonation produced a chimney about 350 ft high (276 ft above the shot point) and 152 ft in diameter (Reynolds, 1971; AEC, 1973a) (Figure 19). Induced fractures extended about 200 ft above the chimney. The chimney and fracturing dimensions were approximately what were predicted prior to the shot. About eight months after the detonation, on April 28, 1970, R-EX was re-entered and sidetracked towards the chimney. Drilling stopped at 8234 ft TD, 192 ft above the shot point, on July 28.

Production testing began on October 4, 1970 and ended on April 23, 1971. 108 days of testing produced 456 mmcf gas (including dilutents CO_2 and H_2); this was equivalent to 10 yrs of production from a conventional well in the Rulison Field (AEC, 1973a).

The Rulison test successfully answered several questions regarding the viability of nuclear stimulation of tight gas-sand reservoirs. 1) The procedure and calculations as applied at Gasbuggy could be applied to the significantly greater depths more typical of Rocky Mountain reservoirs. 2) Nuclear fracturing at Rulison increased the calculated 20-yr per well recovery to 1.8 bcf (AEC, 1973a), although this was significantly lower than pre-shot predictions of 7.1 bcf (Coffer et al., 1970). 3) The seismic effects of the shot within a 20-mi radius were studied and damage-mitigation possibilities were acknowledged (Luetkehans and Toman, 1976). 4) Whereas many geological and engineer-

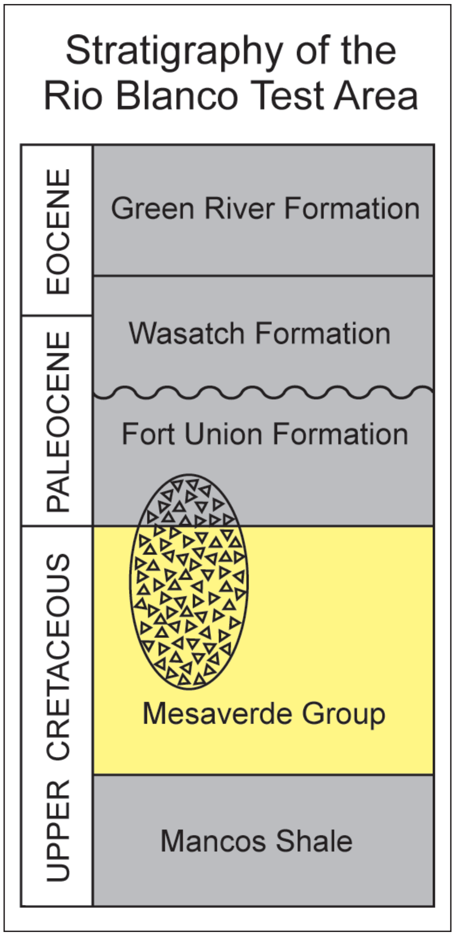


Figure 20. Stratigraphy of the Rio Blanco site.

ing questions were answered, the economic viability (i.e., cost vs. return) had to be addressed. Perhaps the most important lesson learned from Rulison, and one that did not arise at Gasbuggy, was how to address public and political opposition to the technology.

Rio Blanco

Geology

Like the Rulison site, the Rio Blanco nuclear stimulation test site is also located in the Piceance Basin in northwestern Colorado (Figure 16). The site is about 25 mi southwest of Meeker in Rio Blanco County in the Sulphur Creek Gas Field (also called Piceance Creek Gas Field on some maps). The field produces mostly from the Paleocene – Eocene Wasatch Formation with minor production from the Douglas Creek Member of the Green River Formation (Eocene), the Ft. Union Formation (Paleocene), and the Mesaverde Group (Upper Cretaceous) (Figure 20). The field was discovered in 1956 by the Equity 2 Sulphur Creek in sec. 19, T. 2 S., R. 97 W., which was completed in the Douglas Creek at about 2300 ft for 60 bopd (Thurman, 1961). Within the next few years, Equity Oil Company discovered oil and gas in the Ft. Union and Mesaverde. The Rio Blanco test was designed to test the producibility of tight-gas sands in the Ft. Union Formation and upper part of the Mesaverde Group (Williams Fork Formation).

The geology at the Rio Blanco site includes, from top to bottom, the Green River Formation (at surface), Wasatch Formation, Ft. Union Formation, and Mesaverde Group (CER Geonuclear, 1971) (Figure 20). The Green River Formation is of interest because it was being evaluated for its oil-shale resources, and there was concern that the nuclear detonation would negatively impact that exploration and development effort. In the area of the test, the Wasatch is about 2400 ft thick, the Fort Union 800 ft, and Mesaverde ~ 5200 ft. The Ft. Union consists of lenticular sandstone and conglomerate beds interbedded with claystone, shale, and coal and was deposited in fluvial, swamp, and lacustrine environments (CER Geonuclear, 1971). The underlying Williams Fork Formation, in contrast, consists of stacked fluvial sandstones interbedded in gray, green, and maroon shales that Chancellor and Johnson (1988) interpreted as having been deposited in a coastal-plain environment. The lower part of the Williams Fork Formation and underlying Iles Formation (also Mesaverde Group) contain abundant coal beds which are the source of much of the gas in this part of the Piceance Basin.

The Rio Blanco site is near a FERC-designated Mesaverde tight-gas area (Tremain, 1993b) and Boardman et al. (1973) completed detailed studies on the porosity and permeability of the sandstones in the lower part of the Ft. Union and upper part of the Williams Fork Formations. Based on core analyses, they determined an average porosity of 119 ft of net-pay sandstone from 5710 ft to 6473 ft in the emplacement well (RB-E-01) of 8.1% and a log-derived average porosity for the interval 5606 ft to 6782 ft of 9.6%. The weighted averages of the permeabilities in the emplacement well and the nearby Fawn Creek Government No.1 (about 1360 ft south-southwest of RB-E-01) ranged from 0.010 md to 0.029 md. A very limited amount of data is available to explain the origin of the low permeabilities; thin sections of Fort Union and Mesaverde sandstones show moderate amounts of illite and kaolinite and less than 7% carbonates (mostly as grains and not cement) (CER Geonuclear, 1971). In addition to resolving the problem of low permeabilities, other geologic studies focused on identifying areas of increased net sandstone and increased uncompartmentalized sandstone, sandstone-body geometry (e.g., CER Geonuclear, 1971), and changes in permeability due to diagensis.

Detonation

The Rio Blanco test consisted of three simultaneous 33-kt nuclear detonations on May 17, 1973, at 10:00 a.m. MDT. The detonations occurred at depths of 5838 ft, 6230 ft, and 6689 ft in emplacement hole RB-E-01 (Figures 21 A and B) which was located in the SE/4 NW/4 NW/4 sec. 14, T. 3 S., R. 98 W. The primary objective of the test, like that of the Gasbuggy and Rulison tests, was to determine whether commercial quantities of gas could be produced using nuclear-stimulation techniques in a low-permeability gas-rich formation (AEC, 1973b). Secondary objectives of the Rio Blanco test were to: 1) determine whether gas production from a thick gas-bearing interval could be improved by simultaneous nuclear detonations; 2) determine chimney communication and fracture characteristics of the surrounding reservoir rocks; 3) determine the chemical and radiochemical composition of

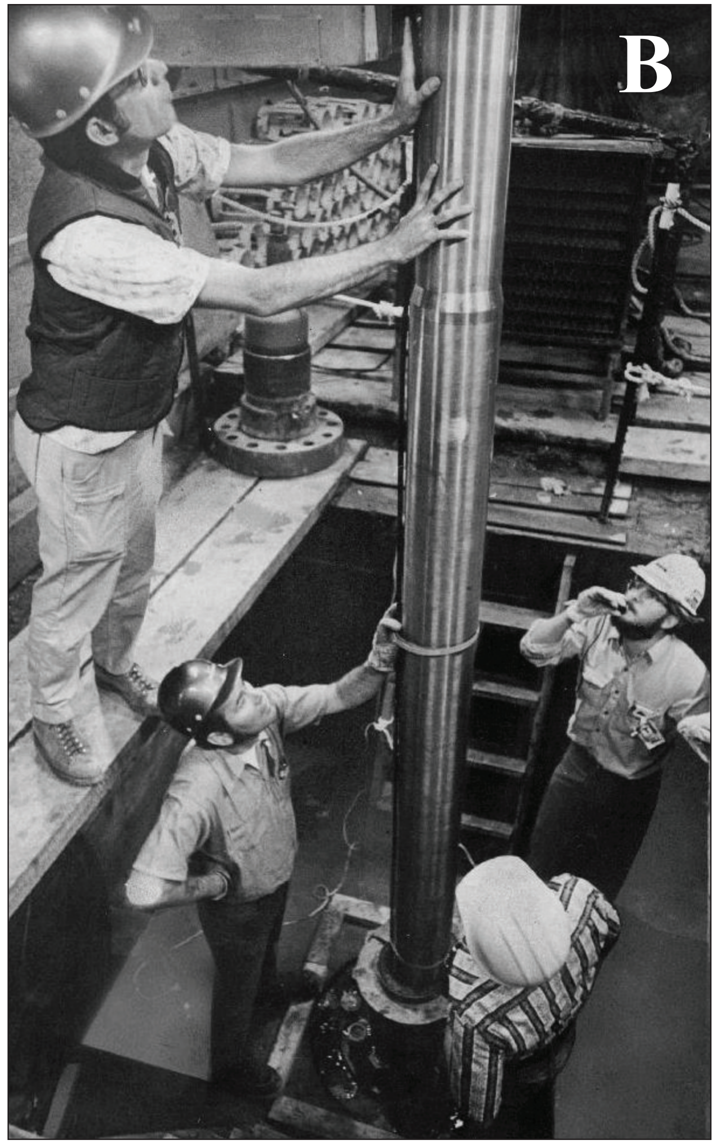


Figure 21. A. Rio Blanco nuclear device suspended in emplacement rig (photo by Kelly Michals, https://flickr.com/photos/rocbolt/8111351250/sizes/l). B. Rio Blanco device being lowered into emplacement well RB-E-01 (photo by Kelly Michals, https://flickr.com/photos.rocbolt/8111352548/sizes/l).

the produced gas; 4) develop a technique that would allow for rapid reentry of the chimney and surrounding fractured rock; and 5) reduce tritium production (AEC, 1973b; Woodruff and Guido, 1974).

The test was a joint government – industry venture between the AEC, Equity Oil Company of Salt Lake City, and CER Geonuclear Corporation of Las Vegas. The AEC selected Lawrence Livermore Laboratory to provide technical advice and the nuclear device. Prior to the test, surface geologic studies were conducted to determine the orientation and extent of the sandstone lenses in the Ft. Union and Williams Fork Formations (CER Geonuclear (1971) and references cited therein) and seismic surveys were run to determine the location of subsurface faults (AEC, 1973b). Two wells, the Fawn Creek Government No. 1 and Scandard Draw No. 1 (about six miles east-southeast of RB-E-01) were recompleted, tested, and logged to more fully understand the reservoir character of the units. A number of environmental reports, beginning with a draft environmental statement, were completed and published.

The AEC (1973b, p. v) described the immediate post-shot effects: “all three explosives detonated and functioned as expected; there has been no inadvertent release of radiation to the atmosphere; no serious architectural or environmental damage oc-

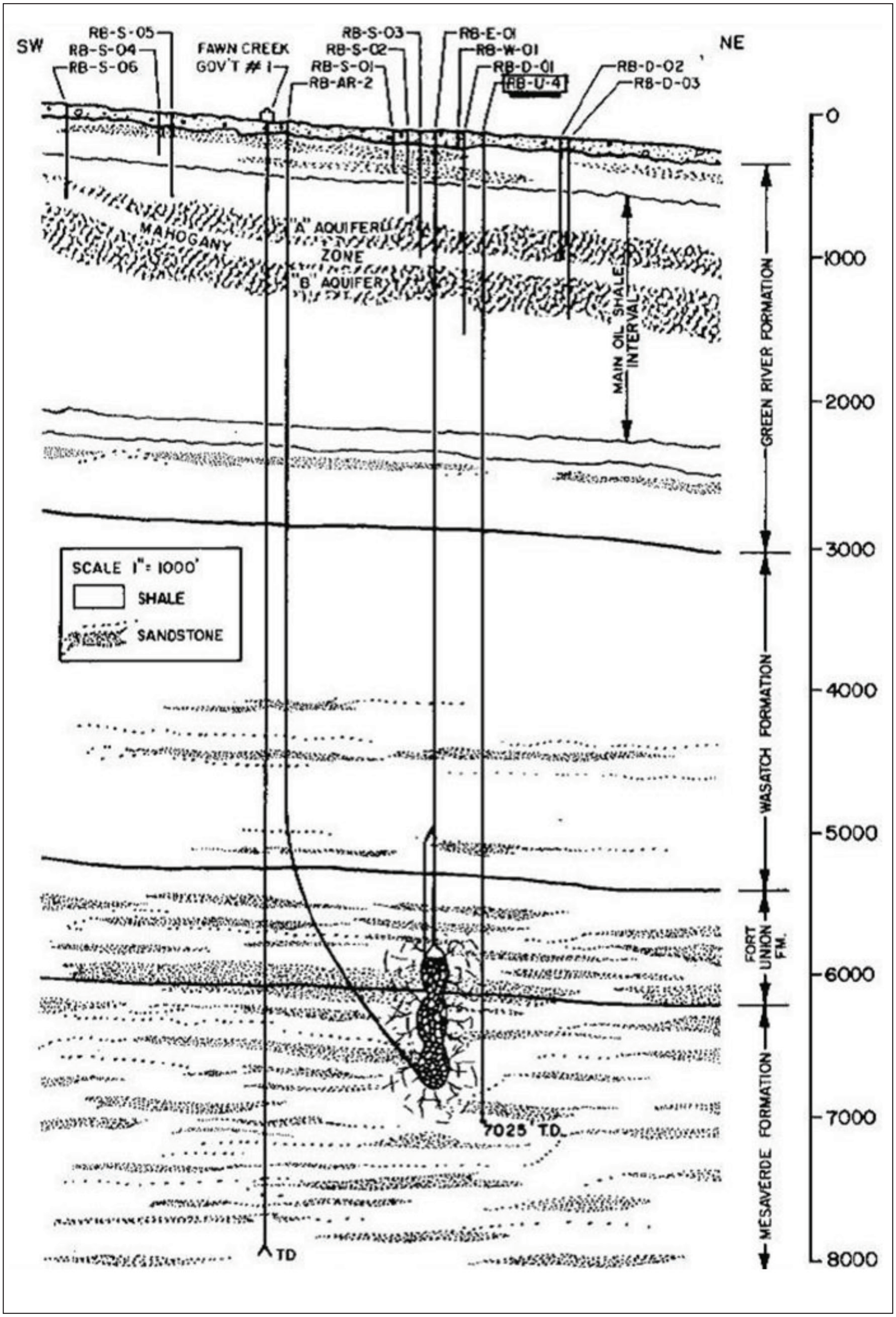


Figure 22. Sketch showing relation of three Rio Blanco chimneys (not connected), subsurface reservoir geology, and post-shot test wells (from powerpoint presentation "Rulison and Rio Blanco Sites," U.S. Department of Energy, Office of Legacy Management, Northwest Colorado Oil and Gas Forum, September 4, 2008. (https://www.google.com/webhp?rlz=1C1GGGE_enUS590US590&ie=UTF-8&rct=j#q=rio+blanco+nuclear=test).

curred; detonation exhibited an equivalent earthquake magnitude of mb 5.4; rockfalls were not observed beyond approximately 20 mi from the emplacement well; some minor bioenvironmental effects were evident within a two-mile radius; (and) claims for seismic damage have been fewer and less significant than anticipated." In addition, 95 aftershocks (maximum magnitude 2.3) occurred within a few thousand feet of the chimney in the first three hours after the detonation and all aftershocks ceased within eight days (AEC, 1973b).

Results

The Rio Blanco shot produced three unconnected chimneys (Figure 22). The depth of the top of the uppermost one is only approximately known. Toman (1975) determined that the "detonation region" was about 250 ft above the shot point, however, neither a void nor chimney rubble was present 117 ft above the shot point. Toman (1975) also calculated the upper chimney had a 66-ft radius. Ballou (1976) calculated the lower chimney had a 70 +/- 10-ft radius. The dimensions of the middle chimney are unknown.

On September 23, 1973, reentry drilling into the emplacement well – RB-E-01 – began. Collapsed casing caused the well to be whipstocked at about 5300 ft. The well TD'd at 5723 ft, about 23 ft below the top of the chimney (Woodruff and Guido, 1974, fig. 48), 5-in. casing was run to 5712 ft, and the well was perforated from 5605 to 5705 ft. Radioactive ^{85}Kr and tritium were detected in the gas and a short-duration production test showed a flow rate just under 6 mmcf/d. A longer production test from November 15 to 21, 1973, produced over 35 mmcf of dry gas, and a second conducted from January 28 to February 15, 1974 produced over 62 mmcf of dry gas. The second test was terminated when the most of the chimney gas was steam and only 1.4 mmcf/d dry gas was being produced (Woodruff and Guido, 1974). A second reason for ending the second test was that the condensed steam contained tritium and the permitted amount of disposed water into the nearby Fawn Creek Government No. 1 well was being approached.

Analysis of the production testing on the RB-E-01 well concluded that the top, middle, and bottom chimneys were not connected (ERDA, 1975), and an alternate reentry well, RB-AR-2 (surface location 1197 ft south-southwest RB-E-01), was directionally drilled into the bottom chimney and tested in December, 1974 in an attempt to explain the lack of communication. In addition, production from the top of the chimney by RB-E-01 was much less than expected, so an additional well, RB-U-4 (surface location 624 ft northeast of the emplacement well) was drilled into undisturbed Ft. Union and Mesaverde sandstones close to the emplacement well.

RB-AR-2 was spudded on June 17, 1974 and TD'd in the lower chimney (Figure 23) at 7051 ft measured depth on October 24. Two cores were collected during drilling at 6723 ft to 6750 ft (21 ft recovered) and 6911 ft to 6925.5 ft (13.5 ft recovered) and a full suite of e-logs were run in the well. The most important result from the core studies was that "the degree of microfracturing in the gas-bearing sandstones is very small, and thus the probable limit of significant explosion-induced permeability enhancement, in this case, does not extend as far as 2.6 Rc" (radius of chimney) (~76 ft) (Ballou, 1976, p. 7). Analysis of the e-logs showed "no significant variation in reservoir characteristics compared to pre-detonation logs from the emplacement well" (Ballou, 1976, p. 7). Production tests on the RB-AR-2 showed the chimney to have a gas volume of only 840 mcf.

RB-U-04 was spudded on September 22, 1974, drilled to 7025 ft and logged. Between December 1974 and August 1976 a number of production tests were run on individual zones in the well. Analysis of the tests and the e-logs showed that the four Mesaverde intervals had an exceedingly low flow capacity, most likely because the water saturation in the sandstones was high enough to preclude effective permeability to gas. Evaluation of three tests in the the upper sandstones – those in the Ft. Union Formation – showed some permeability to gas but had "considerably different characteristics than either predicted prior to the detonation or inferred (from modelling)" (Ballou, 1976, p. 14).

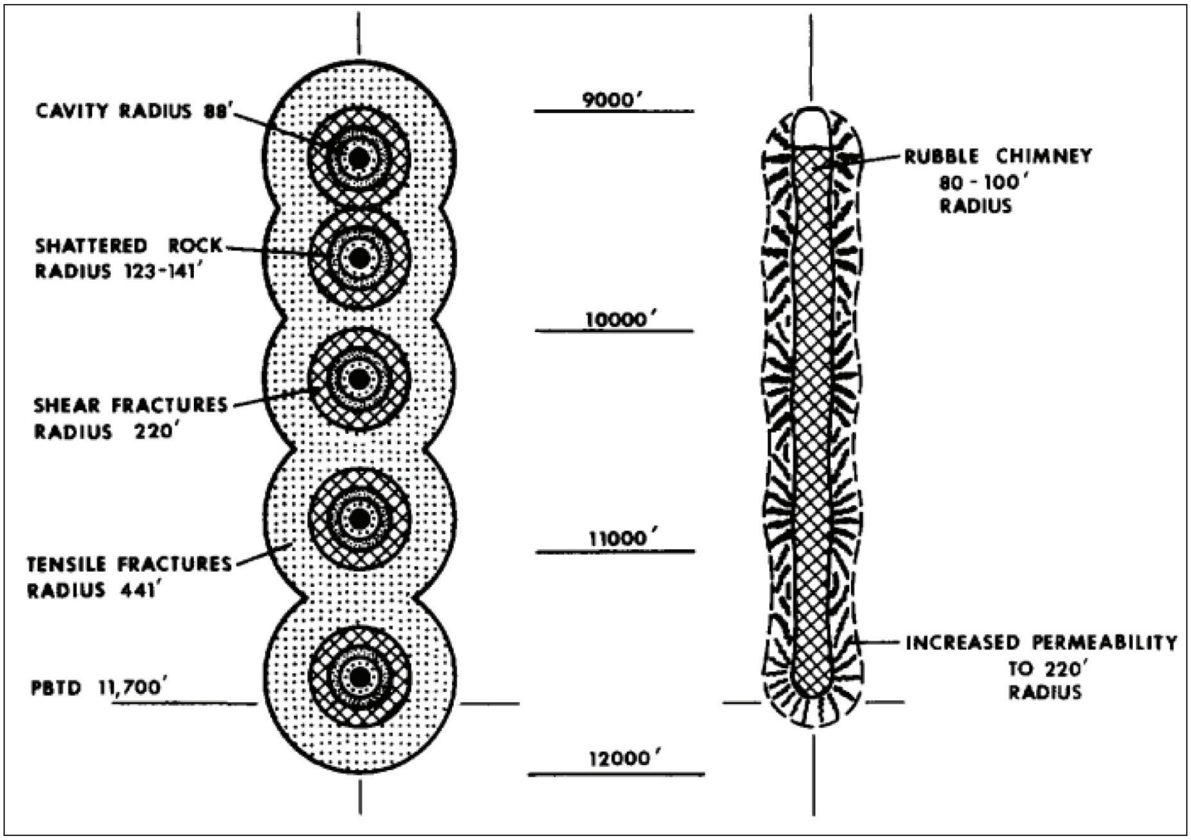
Ballou (1976, p. 15) summarized the Rio Blanco project as follows: "More bluntly stated – if we had known in 1972 what we know now about this site, this project would not have been executed there."

Wagon Wheel, Wasp, and Dragon Trail

The Wagon Wheel, Wasp, and Dragon Trail nuclear gas-stimulation projects were proposed but never completed. All three were designed to fracture the upper part of the Cretaceous and lower part of the Tertiary sections in their respective basins.

The Wagon Wheel test was a joint proposal by the AEC, the U.S. Bureau of Mines, El Paso Natural Gas Company, and Lawrence Radiation Laboratory. One of its principal objectives was to determine the effectiveness of detonating five 100-kt devices sequentially (five minutes apart) to fracture the upper Mesaverde (Upper Cretaceous) and lower Ft. Union (Paleocene) tight-gas-sand reservoirs in the Pinedale Field in the northern part of the Green River Basin (Randolph, 1973; Shaughnessy and Butcher, 1974). The shot points would range from 9220 ft to 11,570 ft deep and would produce a chimney about 2650 ft high with a 100-ft radius (Figure 23). Extensive fracturing and very increased permeabilities were predicted to extend another 120 ft from the edge of the chimney and moderate to slight fracturing another 220 ft beyond that. Randolph (1973) and Shaughnessy and Butcher (1974) estimated that a well drilled into the chimney would produce 21.2 bcf gas in 20 years.

Figure 23. Predicted Wagon Wheel chimney showing chimney and extent of fracturing (from Shaughnessy and Butcher, 1974, figure 9).



The Pinedale Field is located in Sublette County, Wyoming. Exploration and development drilling in the late 1950s and early 1960s identified 3000 ft to 4000 ft of Paleocene to Upper Cretaceous gas-bearing sandstones that were too impermeable to economically produce despite hydraulic-fracture completions. The Wagon Wheel No. 1 (NW/4 sec. 5, T. 30 N., R. 108W) was drilled to characterize the reservoir and serve as a potential emplacement hole. It spudded in October 1969 and TD'd at 19,000 ft in November, 1970. Randolph (1973) evaluated the suitability of the reservoir for nuclear fracturing based on data from the well and on the results from the Gasbuggy and Rulison tests. He concluded that: 1) most of the produced gas over the life of the well would have to come from the fractured zone around the chimney and not the chimney itself; 2) in-situ permeabilities of Rocky Mountain tight-gas sands are only 5% to 10% of laboratory-measured values from cores; 3) fracture-stimulated intervals must be more than 1000 ft thick (thus, multiple detonations must be used in each well) to properly develop the reservoirs; and 4) tritium is the principal radioactive contaminant in the gas.

In addition to the Wagon Wheel No. 1 well, two wells were drilled nearby to characterize the near-surface hydrology and to determine whether or not the induced fractures would intersect any water-bearing zones.

In 1974, Shaughnessy and Butcher reported that the Wagon Wheel project had been delayed because the AEC had not approved funds to develop and test the sequential-firing hardware. (Sequential firing was necessary to comply wth the Threshold Test Ban Treaty, signed in 1974, which limited nuclear detonations to 150 kt.) Subsequent funding for Wagon Wheel was never approved by Congress.

Project Wasp was similar to Wagon Wheel and designed to test the same tight-gas sands on the Pinedale Anticline about 50 mi northwest of Wagon Wheel. The project, proposed by International Nuclear Corp. (representing six companies), was to have detonated a 50-kt device between 11,000 ft and 12,000 ft deep. Wasp did not proceed beyond the definition stage.

Project Dragon Trail was a nuclear stimulation test proposed by Continental Oil Company and CER Geonuclear Corporation in 1966. The test was to have consisted of a 20-kt detonation about 3000 ft deep along the Douglas Creek Arch separating the Piceance and Uinta Basins 16 mi south of Rangely, Colorado (Nordyke, 1969). The project was cancelled by Continental in 1969.

The Demise of Plowshare

The concept of using nuclear explosions for peaceful purposes is almost as old as the Trinity test (1945), but a formal funded program (Plowshare) to investigate such uses was not established until 1957 and the first nuclear test under the program was not done until 1961. Originally shrouded in secrecy (for obvious national security reasons), this early "planning" period of the Plowshare program began during a period of increasing weapons testing, spanned a three-year moratorium on nuclear detonations, and ended when the USSR fired the 57-mt Tsar Bomba – the larest nuclear weapon ever tested – on October 3, 1961. The first Plowshare test followed two month later.

Plowshare consisted of 27 nuclear tests (and many conventional tests) conducted between December 1961 and May 1973 (USDOE, 1997) during a period of intense weapons testing (Figure 2). Most of the early Plowshare tests (1962 to 1968) were designed to determine if nuclear explosions could be used for large-scale earth-moving projects, particularly a new Atlantic – Pacific canal across Central America (Hacker, 1995). The first excavation test (technically called a "cratering shot") – Sedan – was conducted at the NTS but produced radioactive fallout in the upper Midwest. The first Plowshare detonation, Gnome, which was conducted seven month earlier in New Mexico, also produced unexpected results – a geyser of radioactive steam and smoke (Hacker, 1995). The early Plowshare tests were off to an uncertain start.

Later excavation tests, although technically successful, ran into three problems. 1) Tests with higher yields would violate the 1963 Limited Test Ban Treaty. 2) Public safety, particularly with regards to fallout, remained a concern. 3) Earth-moving using conventional explosives was cheaper. Safety and economics continued to be issues of concern to the public and industry partners throughout the remainder of the Plowshare program.

From 1967 to 1973, the AEC and industry partners conducted three underground tests (Gasbuggy, Rulison, and Rio Blanco) to determine if nuclear explosions could be used to fracture-stimulate low-permeability gas-bearing sandstones in two western U.S. petroleum basins. Underground tests had two significant advantages over the excavation tests – because they would be deep there was a greatly reduced threat to public safety and they would not violate any international treaties (Hacker, 1995). Because the tests were conducted outside the NTS, the AEC developed an active public-relations campaign on local, county, and statewide levels. There was little public opposition to Gasbuggy and, in fact, there was public acceptance and encouragement. The growing activism of the environmental movement in the U.S. resulted in significant opposition to Rulison not only to the detonation but to the production-test flaring of the gas (Rubin et al., 1972; Sylves, 1986). The Rio Blanco test followed the passage of the National Environmental Policy Act (NEPA) which required the AEC to issue environmental impact statements (EIS) that would document the predicted on-site and *off-site* consequences of the detonation (Sylves, 1986) as well as address public concerns. The EIS resulted in significant opposition to the Rio Blanco test. Although polls showed most of the local population were in favor of the project, opposition by environmental groups in Denver and Boulder was active and well organized. There was no organized effort to support the test; federal agencies were prohibited from engaging in political debates, and industry sponsors were unwilling to risk public condemnation (Toman and Tewes, 1977). Wagon Wheel was cancelled due not only to local objections but to a broadly based changing national mood regarding nuclear explosions.

The Plowshare program was terminated in September 1975. About $82 million had been spent on Gasbuggy, Rulison, and Rio Blanco (USDOE, 1997). The biggest public concern – that of radioactive contamination of the natural gas and any produced water – remained unsolved or, at best, unexplained. There would be no federal government insurance against claims nor any liability protection (Sylves, 1986). Treaty obligations limited the yield of the detonations. Finally, the cost of nuclear fracture stimulation became prohibitive compared to other developing technologies, specifically, massive hydraulic fracturing. The AEC never disclosed the cost of their nuclear devices, the early-produced contaminated gas could not be sold, and ever-increasing NEPA requirements added delays and costs.

In the end, Plowshare was a technological success but a practical failure. Its promise but meager results collided with a rising tide of public opposition (Hacker, 1995).

QUESTIONS – ADVANTAGES AND DISADVANTAGES

Why did government – industry attempts to prove the viability of fracture-stimulating tight-gas sands using nuclear explosives fail? Was it due largely (or entirely) to the rise of anti-nuclear sentiment in the country or are there other reasons? Could some of the public objections to nuclear frac'ing been overcome with additional research and/or public knowledge? Are there any similarities between how the public viewed the new technology of nuclear frac'ing in the 1960s and how the U.S. public views hydraulic frac'ing today? Could geoscientists and engineers in the 1960s have done more to assuage public anxiety and what might we do today to communicate better with those who want to ban frac'ing? Why did a program that was conceived with the best of intentions and had the full support of U.S. government and industry scientists and engineers fail?

Long (1976) discussed the advantages of using nuclear explosions over conventional methods to produce gas from low-permeability reservoirs. From a hardware perspective, nuclear devices were small and light-weight for the energy they generate and were relatively inexpensive compared to chemical explosives. In addition, the cost of nuclear devices did not vary greatly with yield. Benefits that would have followed the nuclear development of the Rocky Mountain tight-gas fields were mostly economic and included alleviation of a perceived future gas shortage, royalty payments to the federal government, and stimulation of local economies (Rubin et al., 1972).

As the tests progressed, the disadvantages to using nuclear explosions became more obvious. An immediate (and noticeable) effect was that the detonations produced earthquakes (although Randolph (1973) noted that many of the fields proposed for nuclear development were relatively remote and sparsely populated). The most serious problem was the production of long-lived radioisotopes in the produced gas, specifically tritium and ^{85}Kr, as well as large amounts of CO_2, which lowered its Btu value (Long, 1976; Lorenz, 2001). A geologic problem was that the size of the chimney and nature and extent of fracturing outside the chimney were difficult to predict (Long, 1976) and different explosive devices would have to be designed for different types of reservoirs. This was important because post-shot production, most of which came from the fracture zone, was not as good as predicted (Lorenz, 2001).

Additional disadvantages to using nuclear explosions in tight-gas reservoirs were legal and legislative. Would nuclear devices be commercially available at an established price and what security issues would this cause (Long, 1976)? (For example, how would the hundreds or thousands of devices needed for full-field development be transported to the well-sites?) What would be the federal, state, and local spheres of interest and regulations (Toman and Tewes, 1977) and who, if anyone, would insure against damages?

Finally, an enormous disadvantage for nuclear frac'ing over conventional completions was public perception in the context of the Cold War. In October 1961 the largest weapon ever tested on Earth – Tsar Bomba – was detonated by the USSR over the Novaya Zemlya archipelago in the Barents Sea. The 57-mt bomb was ten times the explosive power of all the conventional weapons used in World War II. The Cuban missile crisis in October 1962 convinced many Americans that the world was on the brink of nuclear war and the first communist Chinese test in October 1964 further worried the U.S. public. As a result of these events and the increasing number of weapons tests throughout the 1960s, international treaties limiting different aspects of nuclear tests (including those designed for peaceful purposes) and beginning, perhaps most importantly, with the Limited Test Ban Treaty (1963), were signed. It was in this atmosphere of continued weapons testing and repeated attempts to control those tests that the proponents of nuclear frac'ing had to operate.

Two issues that ultimately doomed Plowshare are irrelevant to modern hydraulic fracturing – profitability and treaty obligations. Horizontal drilling and modern completion techniques have enabled the U.S. petroleum industry to develop formerly uneconomic (and in some cases unrecognized) oil and gas reservoirs; this has provided jobs, made the U.S. more energy independent, and made many companies very profitable. None of the Plowshare fracturing tests made money. In addition, the use of nuclear explosives was governed by international treaties; states regulate hydraulic frac'ing.

SAFETY AND HEALTH ISSUES – THEN AND NOW

Many public safety and health issues are similar in the anti-nuclear and anti-hydraulic frac'ing debates. From the broadest and most general to the most specific, these are:

1. The rise of anti-nuclear sentiment in the U.S. in the 1970s is, in many ways, similar to the increase in climate-change concerns today.
2. Environmental concerns in the 1970s centered around radioactive contamination of the natural gas that was to be produced, marketed, and used and co-produced water. Today, the primary concern is the contamination of groundwater resources.
3. The Viet Nam War and Watergate created a general mistrust of the government in the late 1960s and early 1970s, and government scientists were not immune. Today, large segments of the American public distrust industry and, in particular, "big oil." This includes many, if not all, of the geologists and engineers who work in the petroleum industry.
4. The possibility of an accident that would result in environmental damage or a public health risk might be small for one well but increases significantly with full-field development. This would be true for a nuclear- or hydraulically fracture-stimulated field.
5. The public must be protected from damages caused by frac'ing. Claims resulting from nuclear frac'ing were handled by the AEC. Today, most claims are processed through the legal system and courts.

The introduction of a new technology to the public requires forethought, particularly when public-health and safety issues – real or perceived – are involved. The Gnome and Gasbuggy tests were preceded by extensive public-awareness campaigns that were generally well-received because the public: 1) believed the geologists who said there was an impending natural-gas shortage; 2) believed the scientists and engineers who said the tests were necessary to validate the concept of nuclear frac'ing; 3) believed the AEC who said any radioactivity would be contained; and 4) perhaps under-appreciated the ultimate goal of the tests which, if successful, were to develop a number of Rocky

Mountain petroleum basins. Towards the end of the Plowshare program, the public: 1) no longer worried about a gas shortage or, if they did, the production results of the three tests (Gasbuggy, Rulison, and Rio Blanco) did not convince them that nuclear frac'ing would solve the problem; 2) began to be concerned about the effects of predicted (suggested?) full-field development(*); 3) doubted that the environmental consequences of such a massive project would be negligible; and 4) wondered who would be responsible for monitoring the fields for decades into the future. Are there any lessons to be learned from how scientists and engineers handled or mishandled public concerns in the early 1970s? What can geoscientists and engineers do today to convince the public that hydraulic fracturing is safe if, in fact, it is?

- In the 1970s, nuclear scientists seemed disconnected from (at best) or oblivious to (at worst) the growing anti-nuclear sentiment in the country. This was a mistake. Today, petroleum geologists and engineers should acknowledge the Earth is warming and that man's use of fossil fuels is a major cause. They should also explain that the reliance on these fuels began with the industrial revolution, that fossil fuels are a bridge to more sustainable energy resources (although no one knows how long that bridge is), and ask if we would be willing to do without the many modern petroleum-based conveniences that we enjoy today.

- The issues of radioactive contamination and waste were addressed in the 1970s but remain problems today – Hanford, Washington; Yucca Mountain, Nevada; and Savannah River, South Carolina remain in the news. In contrast, hydraulic fracturing has been a standard industry completion practice for decades, although service companies continue to develop more efficient frac fluids, some of which contain dangerous chemicals. The industry initially refused to identify the chemicals being used in frac job – they were "proprietary" or "trade secrets." This failure to fully disclose is similar to the AEC claming (understandably, given the Cold War mentality) that much nuclear technology and costs were "classified." Today's petroleum industry should disclose the composition of the frac fluids they use and the flowback fluid they recover and how they dispose of or recycle it. In addition, the industry should educate the public that the principal environmental concern is ***not*** the escape or leakage of frac fluid from the producing formation directly into an aquifer, but bad casing or a poor cement job where the well drilled through the aquifer, and that this source of contamination is possible, although unlikely, for any poorly completed or abandoned oil or gas well and not solely frac'd wells.

- The mistrust of industry professionals is a long-term problem and may be part of a general mistrust of science. (One-third of U.S. adults reject Darwinian evolution.) In the 1970s, advocates for nuclear frac'ing failed to enlist any outside scientific organizations to support continued testing. The U.S. petroleum industry would be wise to seek the support of professional and business groups that are independent of and not affiliated with the industry to educate the public. The National Academies of Sciences or Engineering are widely respected and generally viewed as unbiased.

- Unlike the proposed (but never started) nuclear development of the Piceance, Uinta, and Green River Basins, many oil and gas fields throughout the U.S. exist because hydraulic fracturing is economic. In addition, considering the long history of hydraulic fracturing, the number of fields that are fully developed by hydraulic fracturing, and the near-absence of examples of aquifer contamination by wells that were hydraulically fractured, the technique can be considered relatively safe. However, industry must acknowledge that it is not 100% safe and that efforts are always being made to exceed regulators requirements. The blame for accidents must be accepted, damages must be paid, and every effort to see that the problem never recurs must be transparent.

- During the Plowshare tests, the AEC acknowledged that structures could be damaged by the detonations and paid private-property owners for their losses. Because full-field nuclear development never occurred, the issue of liability for large-scale long-lived subsurface contamination became moot, but it was discussed. At the present time there do not appear to be any plans for the long-term monitoring of groundwater resources above hydraulically fractured oil and gas reservoirs. A consequence of this is that long-term liability issues remain. A government (state or federal) – industry program to monitor the near-surface water resources before, during, and after the development of a hydraulically fractured petroleum reservoir and the acceptance of liability if there are damages might lessen some present objections to hydraulic fracturing.

(*) 140 to 280 wells to develop the Rio Blanco Field (AEC, 1972); 5665 wells to develop the Piceance, Uinta, and Green River Basins (AEC, 1973c); 13,000 wells to develop all the Rocky Mountain tight-gas basins (Kreith and Wrenn, 1976).

SUMMARY

What can petroleum geoscientists and engineers learn from the Plowshare program about working with the public?

1. Acknowledge that there are global consequences to using fossil fuels and that they are only a "bridge," but a necessary "bridge."

2. Fully disclose the nature of the material being injected into and withdrawn from the subsurface and educate the public about the real sources of possible contamination.

3. Seek the vocal support of non-petroleum-industry professionals.

4. Educate the public about the history of hydraulic fracturing and explain that it is safe but can always be made safer.

5. Financially protect the public from any potential (however unlikely) consequences of hydraulic fracturing.

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Biographical Sketch

Neil Suneson has worked for the Oklahoma Geological Survey since 1986, when he and some colleagues started mapping the frontal belt of the Ouachita Mountains and the southern part of the Arkoma Basin as part of the USGS-sponsored COGEOMAP and later STATEMAP programs. After working in the Ouachitas, he did some reconnaissance mapping in northwestern Oklahoma and more detailed mapping in the Oklahoma City metro area.

Neil Suneson
Oklahoma Geological Survey

When the Survey became part of the Mewbourne College of Earth and Energy at OU, more of Neil's time was devoted to teaching (including the School of Geology's summer field camp outside of Cañon City, Colorado) and advising students on their theses. His interests range from the Late Tertiary geology of the Oklahoma Panhandle to the Early Paleozoic geology of the Broken Bow uplift in southeastern Oklahoma and everything in between. He even likes (some) igneous rocks.

Prior to working for the Survey, Neil was a petroleum development geologist with Chevron USA where he worked on the Lost Hills Oilfield. He also worked with Chevron Resources Company in geothermal exploration throughout the western U.S. All his college degrees are in geology. He received at B.A. from Amherst College in 1972, an M.S. from Arizona State University in 1976, and a Ph.D. from the University of California – Santa Barbara in 1980. His dissertation, largely funded by the U.S. Geological Survey, was based on mapping in the highly extended terrane of west-central Arizona.

Shale Shaker

OCGS Oklahoma City Geological Society

10 Northwest Sixth Street
Oklahoma City, OK 73102