On October 30, 1961, about one month before the first US Plowshare nuclear test, a specially designed Russian Tu-95V bomber took off from an airfield on the Kola Peninsula for the Mityushikha Bay nuclear testing range.

Tsar Bomba was the most powerful explosive device ever detonated – 57 mt*

- 1500x combined power of Hiroshima and Nagasaki bombs
- 10x combined firepower of all WWII explosives
- 10% of combined yield of all nuclear tests to date
- Fireball reached 7 miles high, 5 miles in diameter, visible 620 miles away
- Mushroom cloud was 40 miles high, cap was 59 miles in diameter

This was the context under which the US Plowshare program and nuclear frac'ing was held.

*1 mt = 1,000,000 tons of TNT

History of Nuclear Frac’ing in the US: Have We Learned Anything?

Neil H. Suneson
Oklahoma Geological Survey

Department of Geosciences
University of Tulsa
September 23, 2015

Why try nuclear frac'ing at all?

1. Perceived gas/energy shortage.
2. Enormous resource in Cretaceous tight gas sandstones in Rocky Mountains region.
3. Jobs. By early/mid 1960s, writing was on the wall for those involved in nuclear weapons research and production.

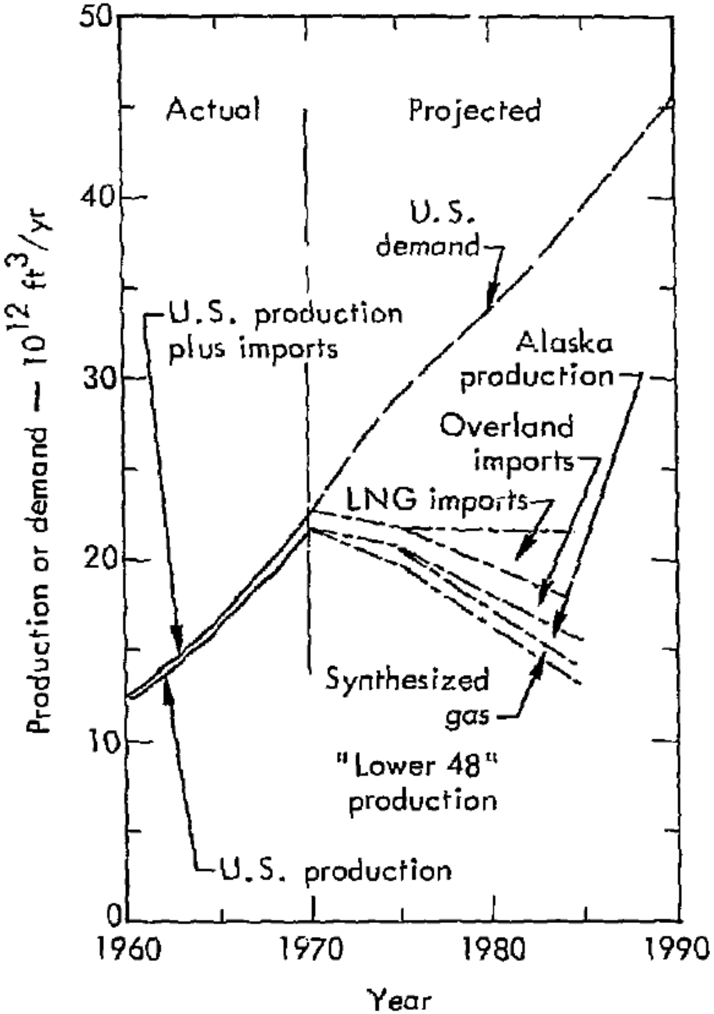


Fig. 1. U.S. natural gas demand and supply.[7]

Projected Demand vs. Supply for Natural Gas

(source: Future Requirements Agency, Denver Research Institute, 1971)

Perceived shortages created by price controls. 1954 – SCOTUS decision says gas producers subject to oversight by Federal Power Commission. FPC attempts to institute "cost of service" vs. "market value" rates. But too many producers. 1960 – FPC attempts to set "area wide prices" based on 1959-1960 contract prices. Was much more difficult than anticipated due to widely varying production costs within a single area. Thus, prices frozen at 1954 or 1959 levels for many areas. **Result: increased demand (gas cheap) but little incentive to produce.**

and in the public media: Fortune magazine, Nov. 1969

"Nuclear explosions may blast a path to adequate gas reserves."

Nuclear explosions may blast a path to adequate gas reserves. In Austral Oil Co.'s Project Rulison in September this forty-kiloton charge was lowered 8,400 feet into gas-bearing sandstone near Rifle, Colorado.

Not Enough Gas in the Pipelines

Natural gas now supplies one-third of the nation's energy requirements. But a prospective shortage of supplies may deflate expectations of an expansive future. And federal price regulation is not helping.

by Anthony Liversidge

The blue flame of natural gas burned ever more brightly in the U.S. in each year of the Sixties. Barely thirty years ago, natural gas was flared at the wellhead as an unwanted byproduct of the search for oil. Today it supplies an astonishing one-third of the total energy used by the U.S. economy—as much as is supplied by oil, and nine times as much as by hydroelectricity. Spurred by the relative cheapness and cleanness of gas, the market has outstripped all but the rosiest projections. Ten years ago, 32 million customers burned 12 trillion cubic feet of gas. This year over 40 million customers will consume more than 20 trillion cubic feet. In the same period the value of the industry's gross plant has almost doubled, from $20 billion to $38 billion.

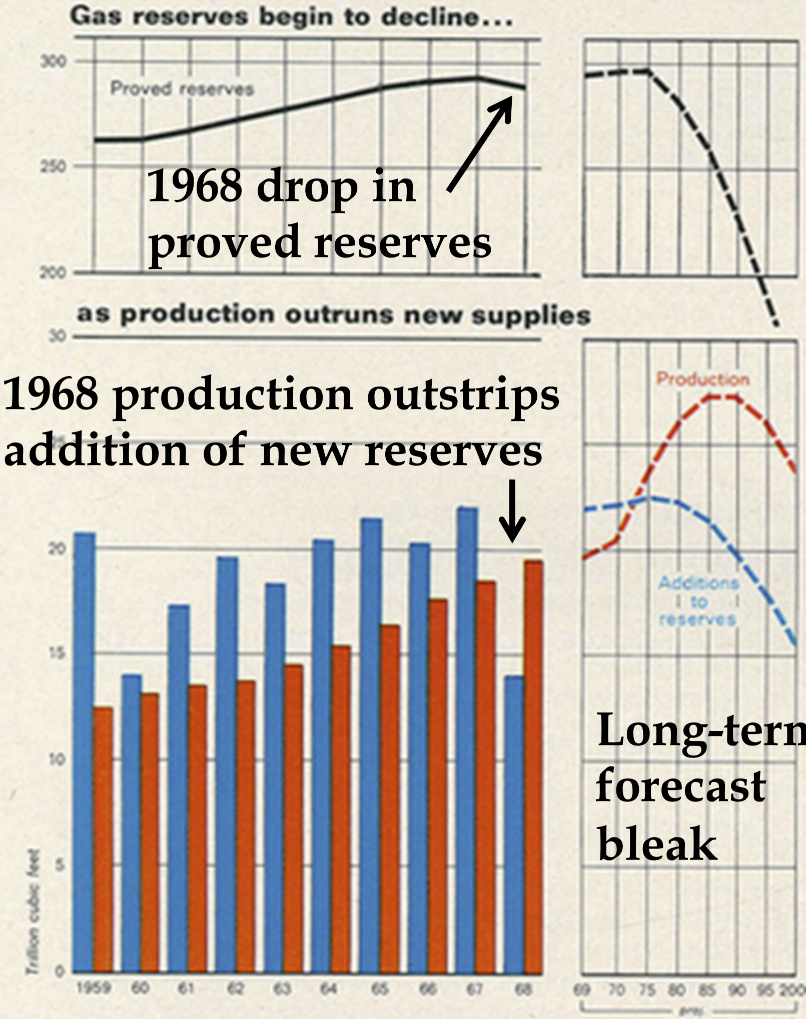
The advantages of gas over competing fuels would seem to point toward a future even more brilliantly illuminated by the "immaculate fuel." Nuclear energy, an alternative source of power, is coming along much more slowly than was expected a few years ago (see "A Peak Load of Trouble for the Utilities," page 116). The future for oil and coal is clouded by the fact that they contain high amounts of sulphur, a major cause of dirty air; natural gas contains virtually none.

New uses of gas are ballooning with promise. The antipollution car of the future may be powered not by steam or electricity, but mainly by natural gas. A $360 kit will readily convert an average car to run on compressed gas, and such a kit is now on the market. Since such conversion could rescue the internal-combustion engine, the implications are dramatic, as Governor Reagan obviously appreciated when shown one of the forty converted cars that Pacific Lighting Corp. has put on the California roads. (He is said to have cried "By golly!") Great potential could also lie in the electrochemical fuel cell, which produces electricity from gases. Three such cells, designed by Pratt & Whitney Aircraft, provide power for the Apollo spacecraft. In fact, an economy entirely driven by gas is not far beyond present technical capabilities.

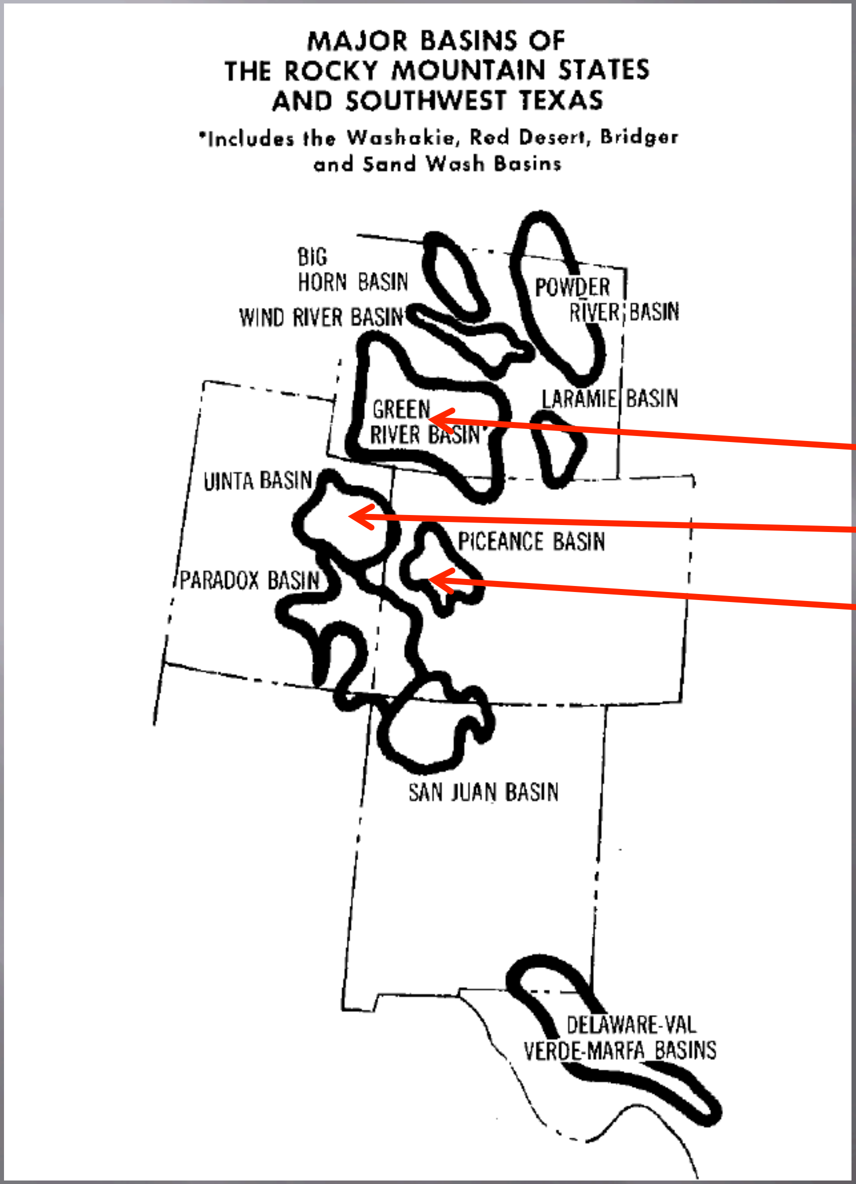
All these glowing prospects, however, are dimmed by one more immediate concern. At the beginning of what could be its biggest stage of growth, the gas industry is about to run short of its raw material. This crisis in supply was first signaled some twelve years ago, when the rate of drilling oil and gas wells began to level off, while production and consumption continued upward. Last year for the first time, proved reserves of gas in the U.S., the on-the-shelf inventory of the industry, declined, while production outran new discoveries. Now major distributors in the East are having difficulty lining up new supplies for the growth in demand projected beyond 1970.

One composite estimate by eleven major pipeline companies that gather gas from the fields recently put the shortfall for the winter of 1970-71 at about 2 billion cubic feet daily of unsatisfied new demand. Some scattered local shortages, indeed, may already be appearing. Northern Natural Gas Co., a big pipeline company in Omaha, is trying to withdraw a pipeline permit application it made recently because, it says, it did not have sufficient reserves to feed the projected line. While current reserves can be

The Threat of Shortage Looms



Last year, total proved gas reserves in the U.S. fell for the first time (upper chart). Climbing production (red bars, lower chart) outstripped new additions to reserves (blue bars) in 1968. This may be temporary, but the projection of long-term trends shows that production will eventually have to decline unless new sources are opened up. The forecasts were made by Dr. Martin A. Elliott of Texas Eastern Transmission Corp. and Dr. Henry R. Linden of the Institute of Gas Technology.



Reserves of Natural Gas from Fracturing Techniques

(source: Natural Gas Supply Technology Task Force, National Gas Survey, US Federal Power Commission, 1973)

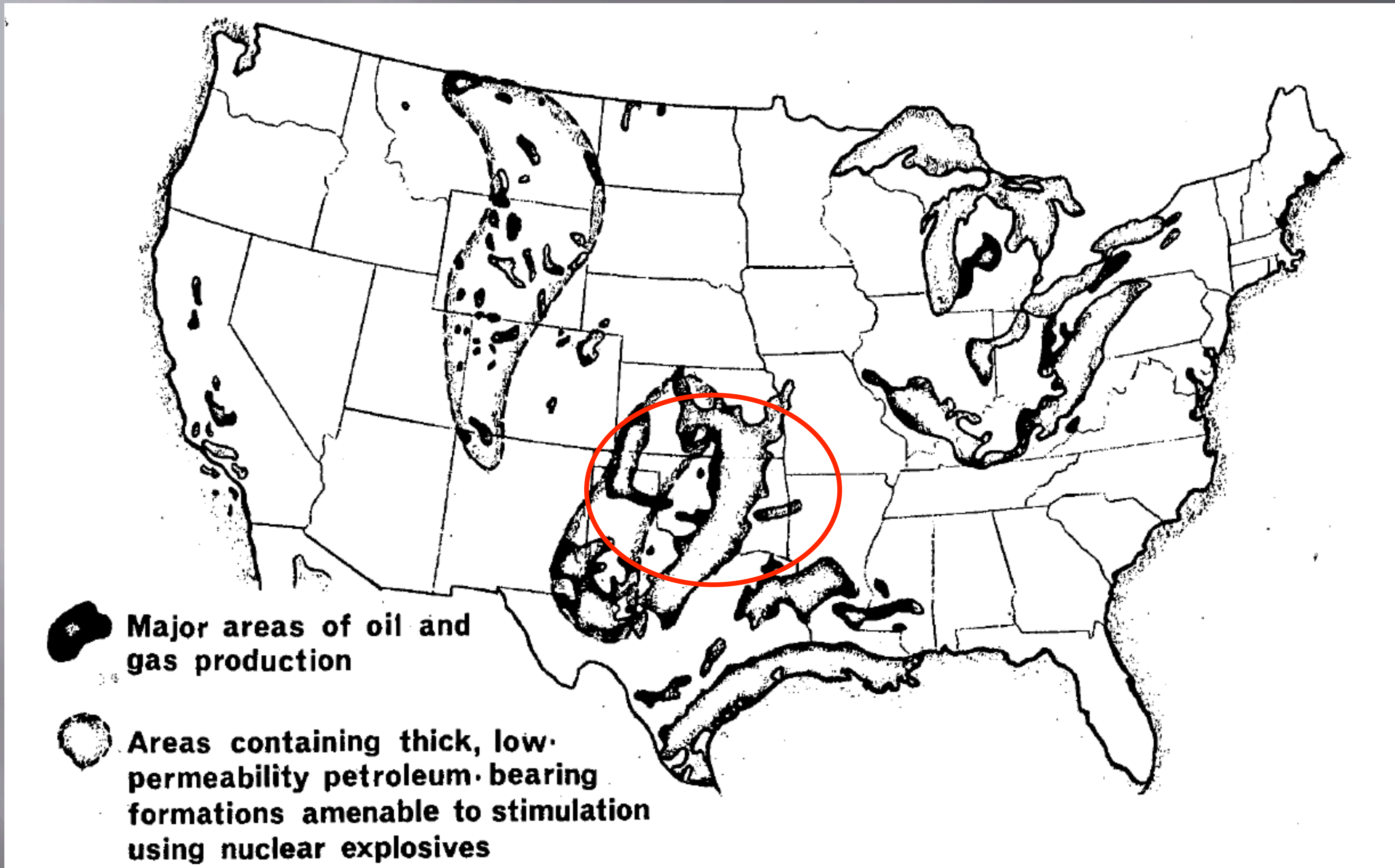
96-120 tcf

60-75 tcf

84-105 tcf

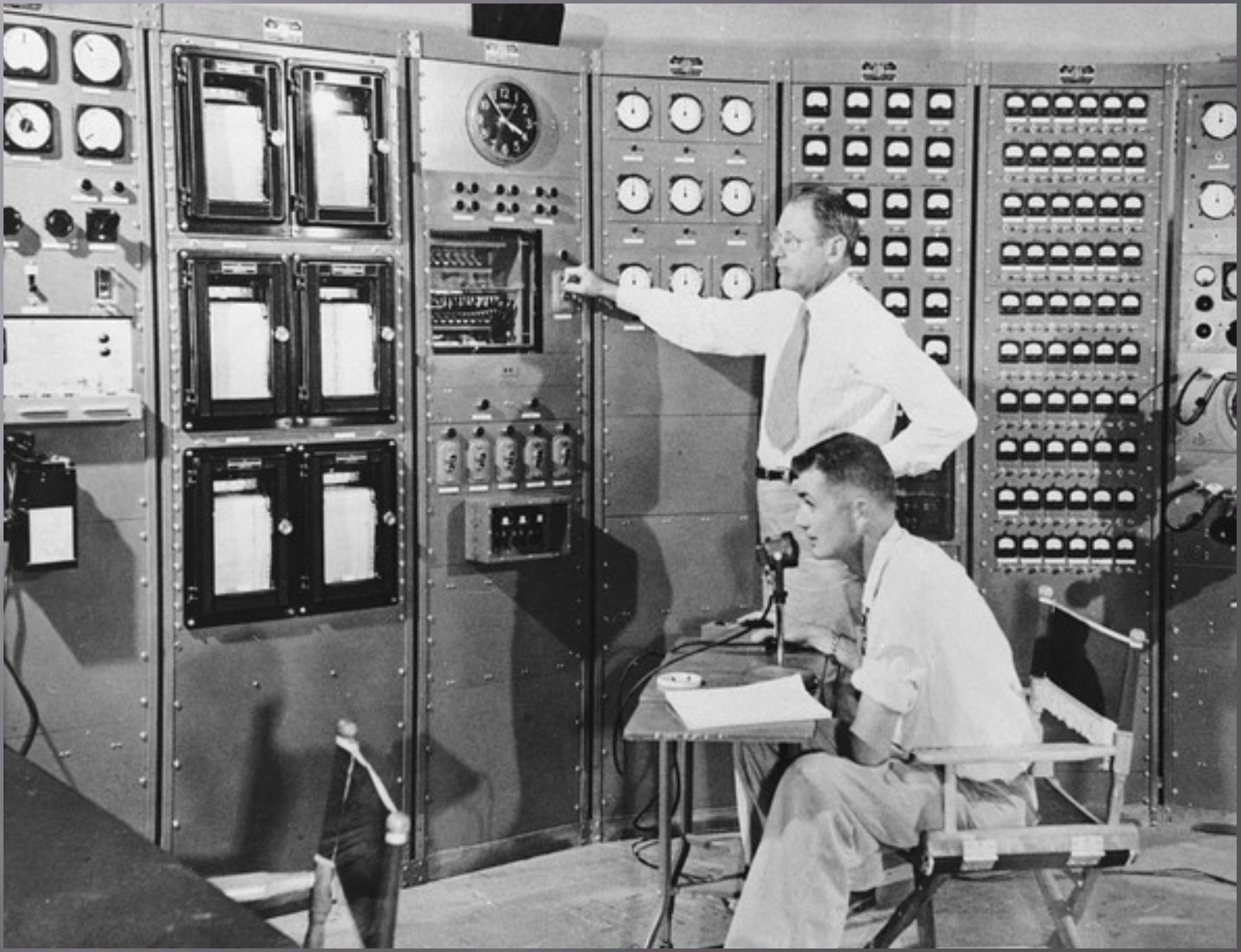
Remember these 3 basins:

Will return to at end of talk.



From "Hydraulic Fracturing" by G.C. Howard and C.R. Fast
Society of Petroleum Engineers of AIME, 1970

Jobs. The Plowshare program and nuclear frac'ing in the context of the Cold War.

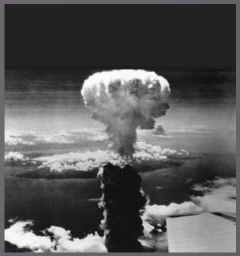


PROJECT PLOWSHARE (27 nuclear tests, 1961-1973)

"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." (Isaiah, 2:4)

- Rubblize ore deposits for *in situ* leaching
- Strip overburden from mineral deposits
- Store water in rubble chimneys
- Store gas in rubble chimneys
- Accelerate groundwater recharge, connect aquifers
- *In situ* retorting of oil shales
- Develop tar sands in Alberta
- Fracture hot dry rock for geothermal energy
- Fracture tight gas sands
- Excavations
  - Harbors, canal through Nicaragua
  - Highways, railroads, waterways through mountains
  - Re-routing river systems

Pre-Plowshare Cold War Milestones – The Setting for Nuclear Frac'ing



1945. July. Trinity test, NM. 21 kt*.
August. Hiroshima, Japan. 15 kt.
Nagasaki, Japan. 21 kt.

1946. June. US Able. First post-war nuclear test. Bikini Atoll. 21 kt.

1949. August. First USSR nuclear test. 22 kt.

1952. October. US Ivy Mike. First thermonuclear test. Enewetak Atoll. 10.4 mt*.

1953. US stockpile 1756 weapons, 2800 mt. (192,000 Hiroshimas)

1954. February. Castle Bravo thermonuclear test. Largest (15 mt) by US. Serious fallout accident. Bikini Atoll.

*1 kt = 1000 tons of TNT; 1 mt = 1,000,000 tons of TNT

Mid-1950s. US nuclear production consumes 6.7% of total nation-wide electrical power; exceeds combined capital investment of Bethlehem Steel, US Steel, Alcoa, DuPont, Goodyear, and General Motors.

1960. US nuclear arsenal at 20,434 weapons yielding 20,000 mt (1.3 million Hiroshimas) (peak megatonnage)

1961. June to November. Berlin crisis.

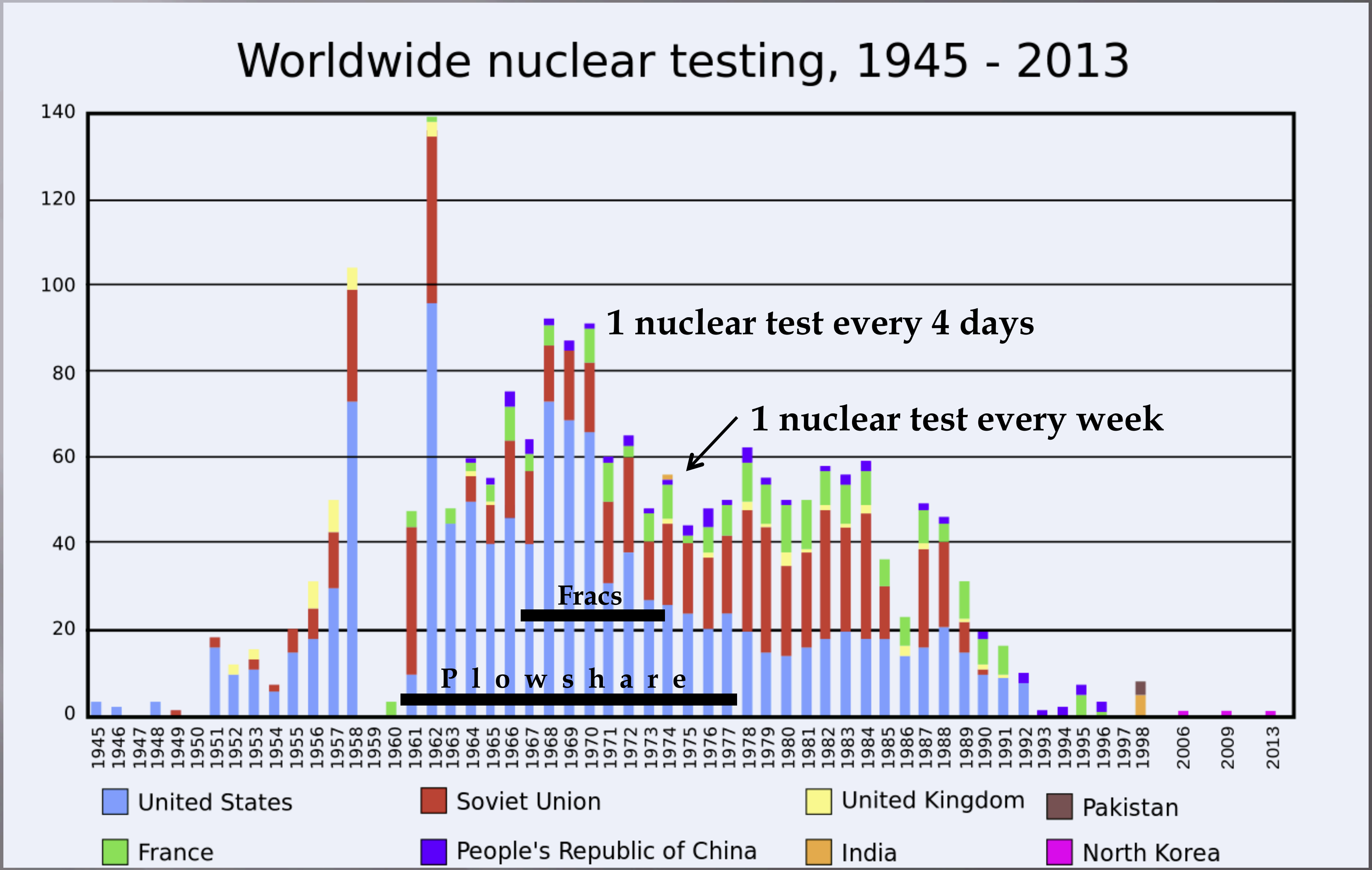
October. Tsar Bomba. USSR. Largest nuclear weapon ever tested (57 mt.)

December. Gnome test (1st Plowshare)

1962. October. Cuban missile crisis.

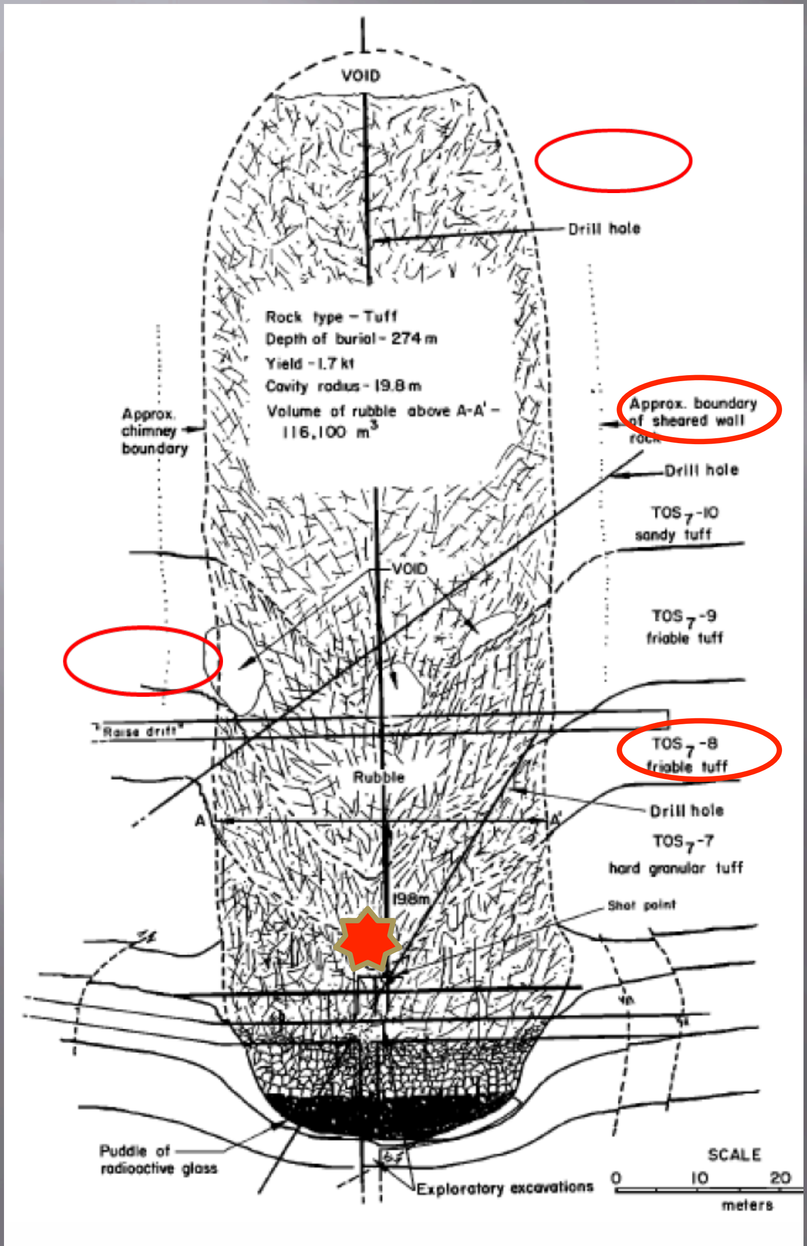
1967. US nuclear stockpile peaks at 31,255 bombs and warheads.

1967. December. Gasbuggy nuclear frac'ing test. Farmington, NM. 29 kt.



The context of Plowshare and the nuclear-frac'ing tests

Rainier Test – September 19, 1957



1.7 kt, 900 ft deep in bedded tuff at NTS

A weapons test, first data on what underground nuclear explosion would do to surrounding rock.

1,000,000º K few msecs after detonation
7,000,000 bars

At first, cavity lined w/ ~4 in. of melted rock. Cavity stood long enough – 30 sec to 2 min - for fluid to flow down sides and drip from roof to form radioactive puddle at bottom.

Then collapse, progressing vertically.

Envelope of fractured rock (w/ increased permeability) extending away from collapse breccia.

Origin of Chimney and Reservoir Model

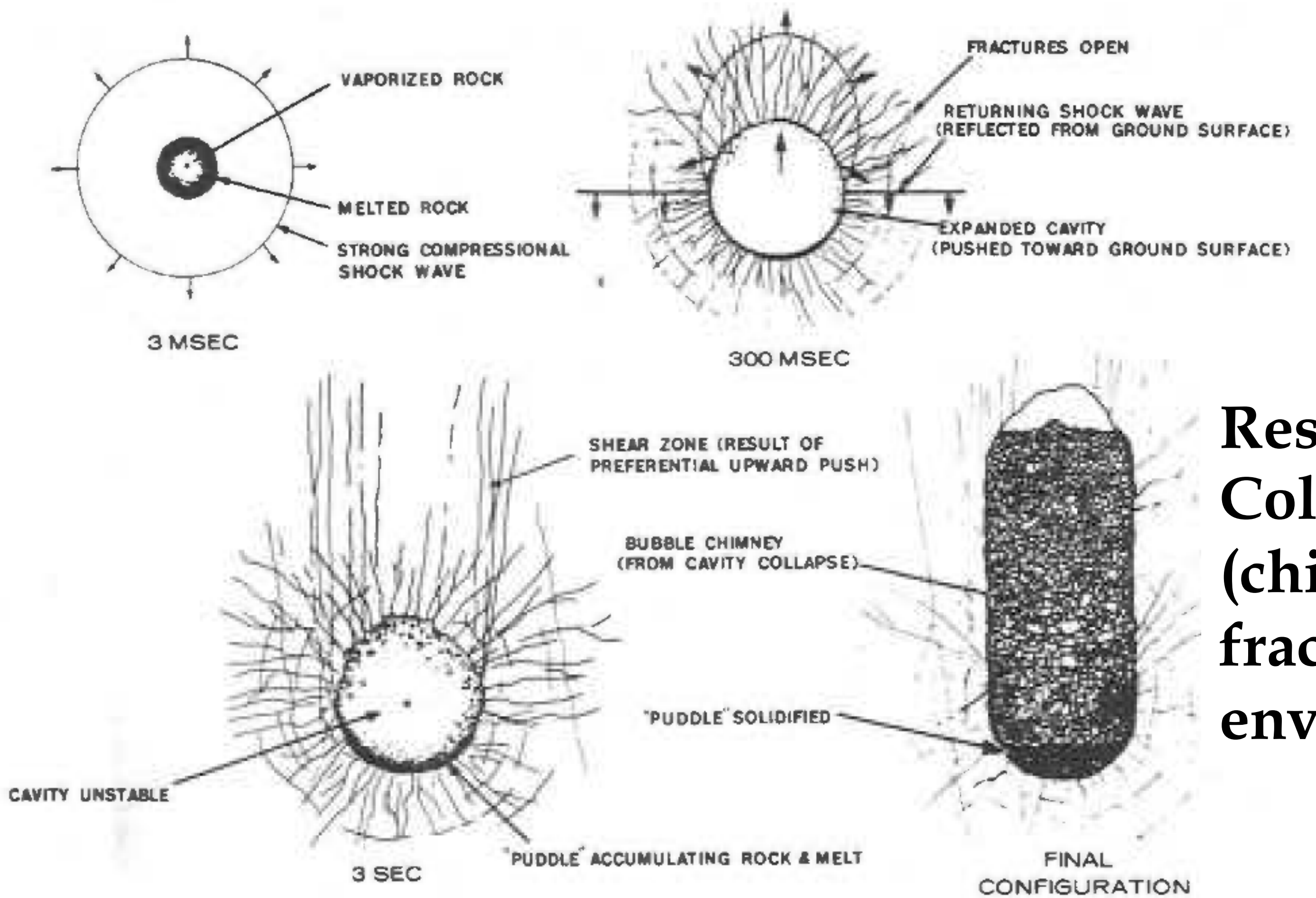


Fig. 1. Cavity chimney-formation history for contained nuclear explosive.

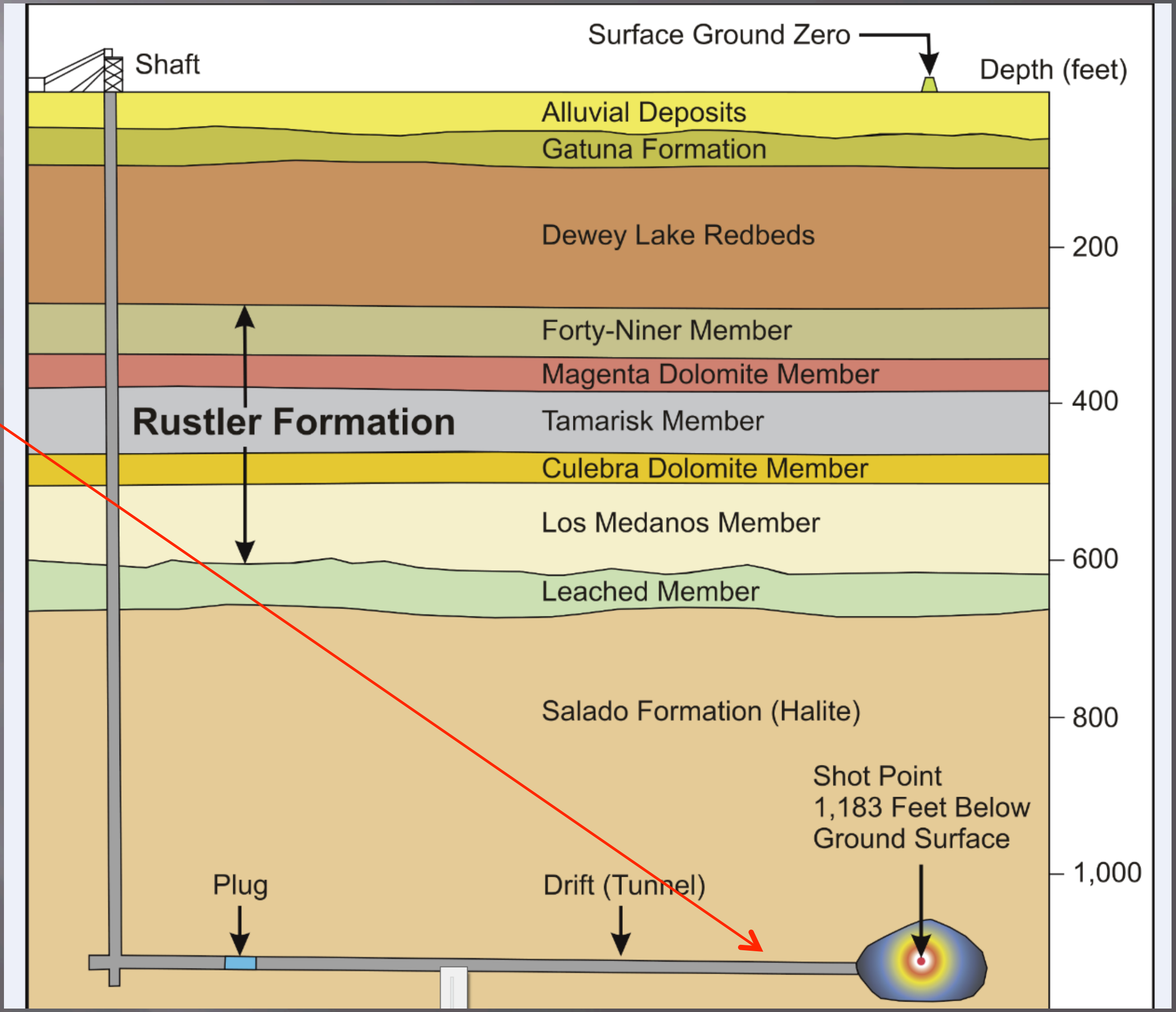
Reservoir: Collapse breccia (chimney) and fractured envelope.

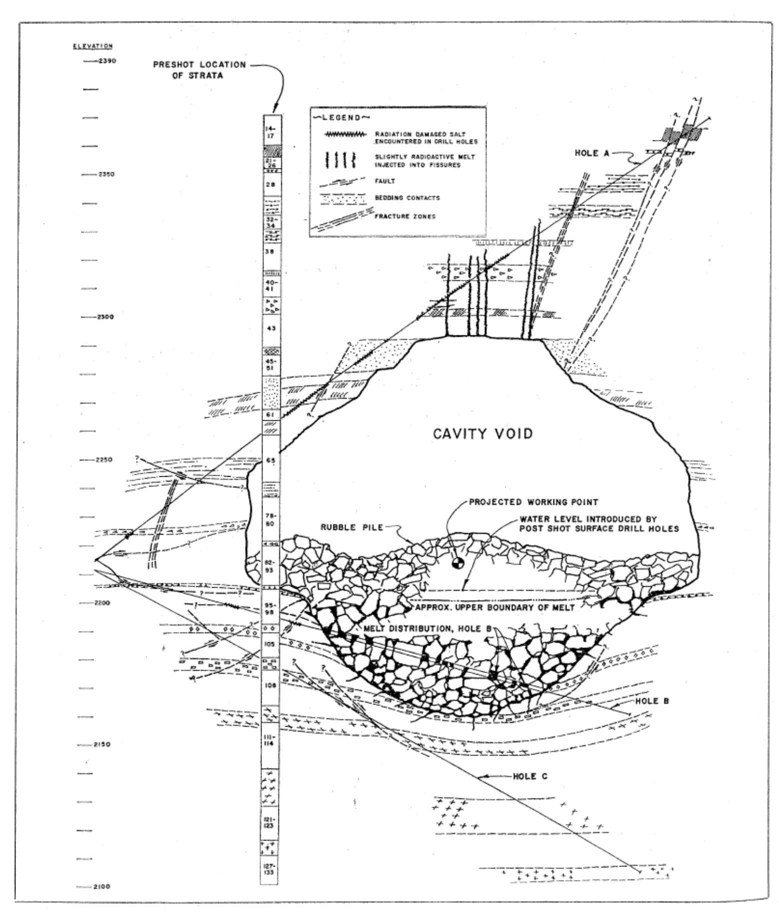
Gnome Test – First Plowshare Detonation
Eddy County, New Mexico
December 10, 1961, 3.1 kt

Goals:
1. GeoT energy from molten salt?
2. Mine radionuclides?
3. Neutron physics
4. Geophysical characteristics of salt
5. EQs vs. nuclear explosion

H/C samples in drift:
1. Carbs increased por and perm; Sss decrease in perm, no change in por
2. Shock wave, radiation little effect on oil spls

Results:
Details of cavity formation, radial fracturing and along partings.



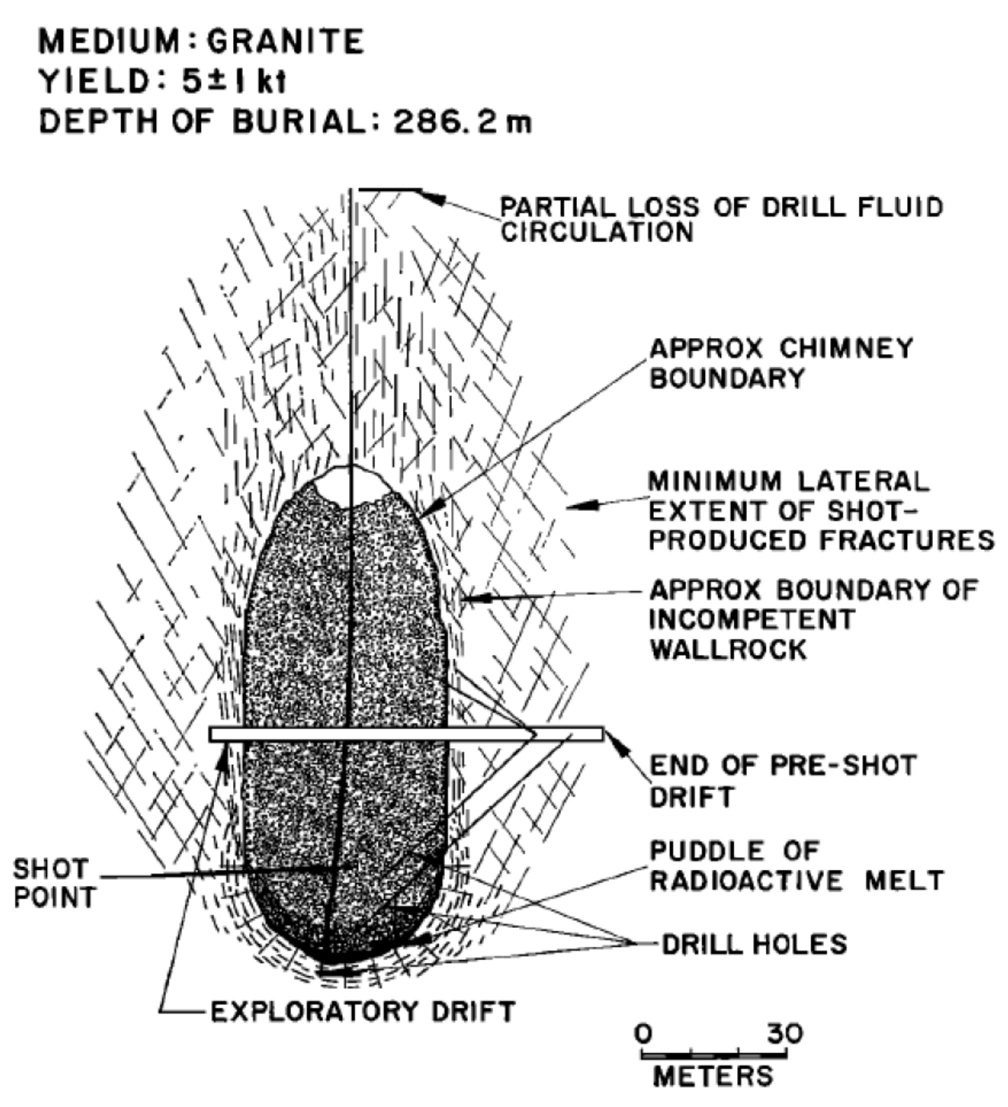


Cross section through Gnome cavity

Interior of Gnome cavity – ~150 ft in diamter, 70 ft left open

The Gnome cavity was entered about 5 months after the detonation. The radiation level was about 20 mREM/hr (average chest X-ray is 2 mREM).

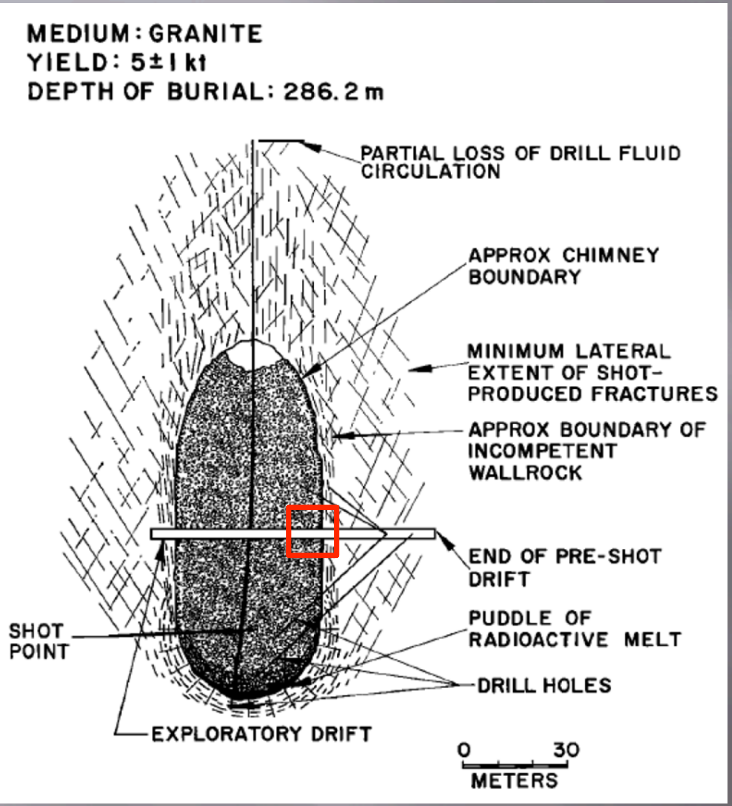
Hard Hat test, NTS
February 15, 1962, 5.7 kt



Short (1966) studied bulk density, porosity, sonic velocity, Young's modulus, permeability, crushing strength, and magnetic susceptibility as function of distance from shot point.

Also defined "fracture index."

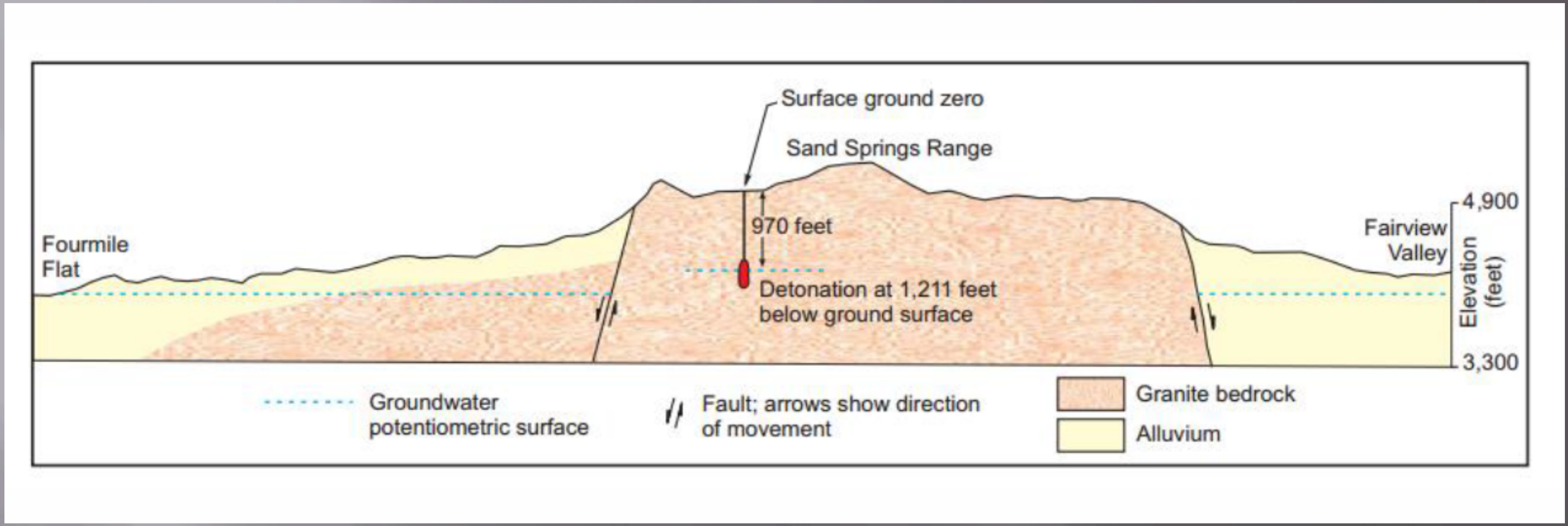
Based on this and Rainier tests, Boardman et al. (1964): fracs extend 2 to 3 cavity radii laterally, <1.5 Rc below, and 6 to 8 Rc above shot point.
Also, cavity size NOT based on rock type, but device yield, bulk density of rock above charge, burial depth, and amount of gas-producing materials (typically water) near shot point.



Brecciated granodiorite in Hard Hat chimney 89 ft above shot point and 10 ft inside chimney.

Sedan excavation test (Plowshare), July 6, 1962, NTS.
104 kt thermonuclear device.
Largest manmade crater in US. 1/3 diameter, 1/2 depth of Meteor Crater.
Fallout contaminated more US citizens (mostly in Iowa) than any other test. Produced 7% of total US fallout during all NTS tests.
Killed concept of using nuclear explosives for excavating.

Shoal test, October 26, 1963. 12 kt.
Vela Uniform program.
Sand Springs Range, 28 mi SE of Fallon, NV

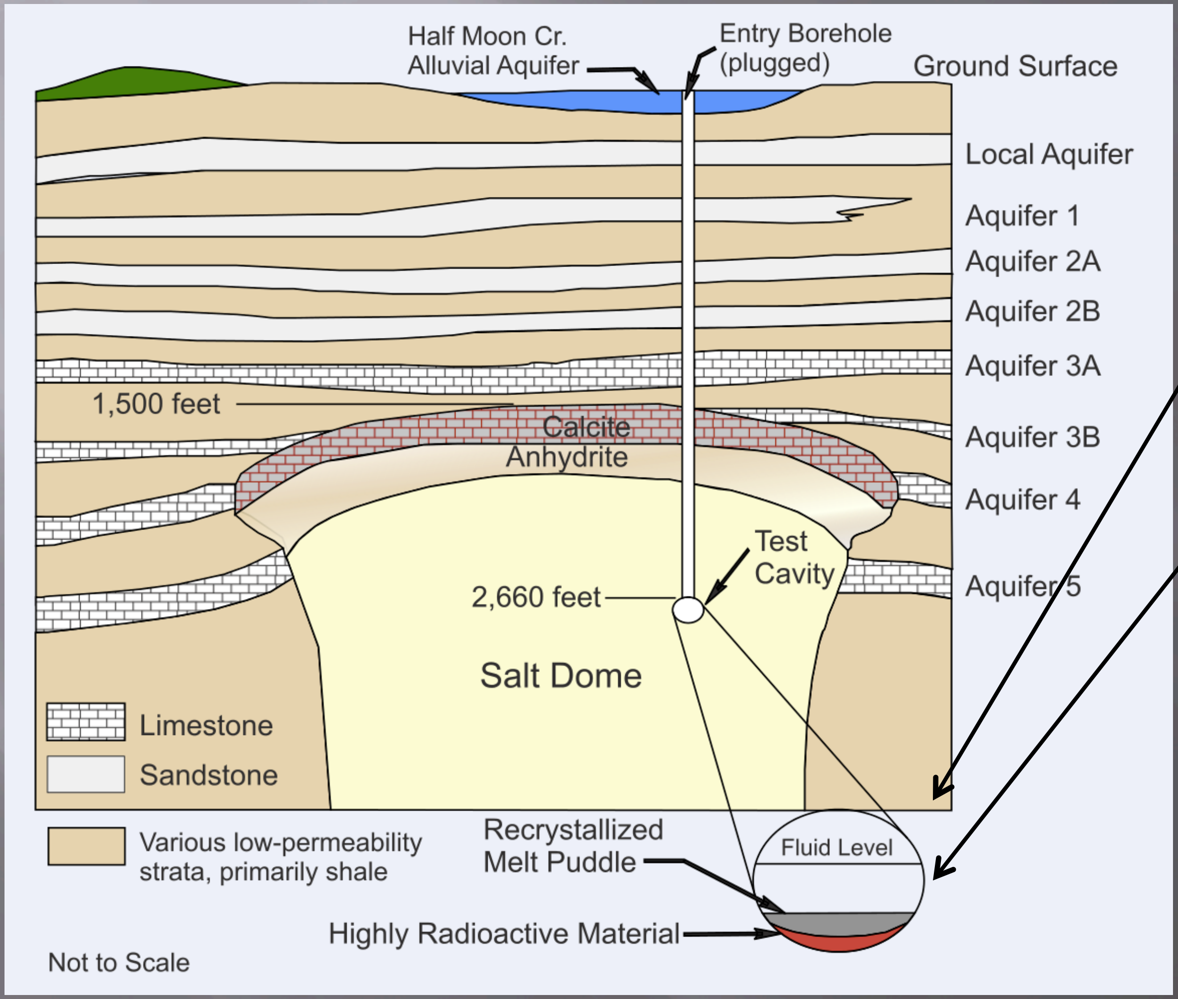


Purpose to identify and locate underground nuclear explosions and distinguish them from natural earthquakes.

Produced rubble chimney about 356 ft high.

Did not trigger any earthquakes, despite having been conducted in area with recent fault.

Salmon test, October 22, 1964, 5.6 kt. Vela Uniform program. Only test in eastern US – near Hattiesburg, MS

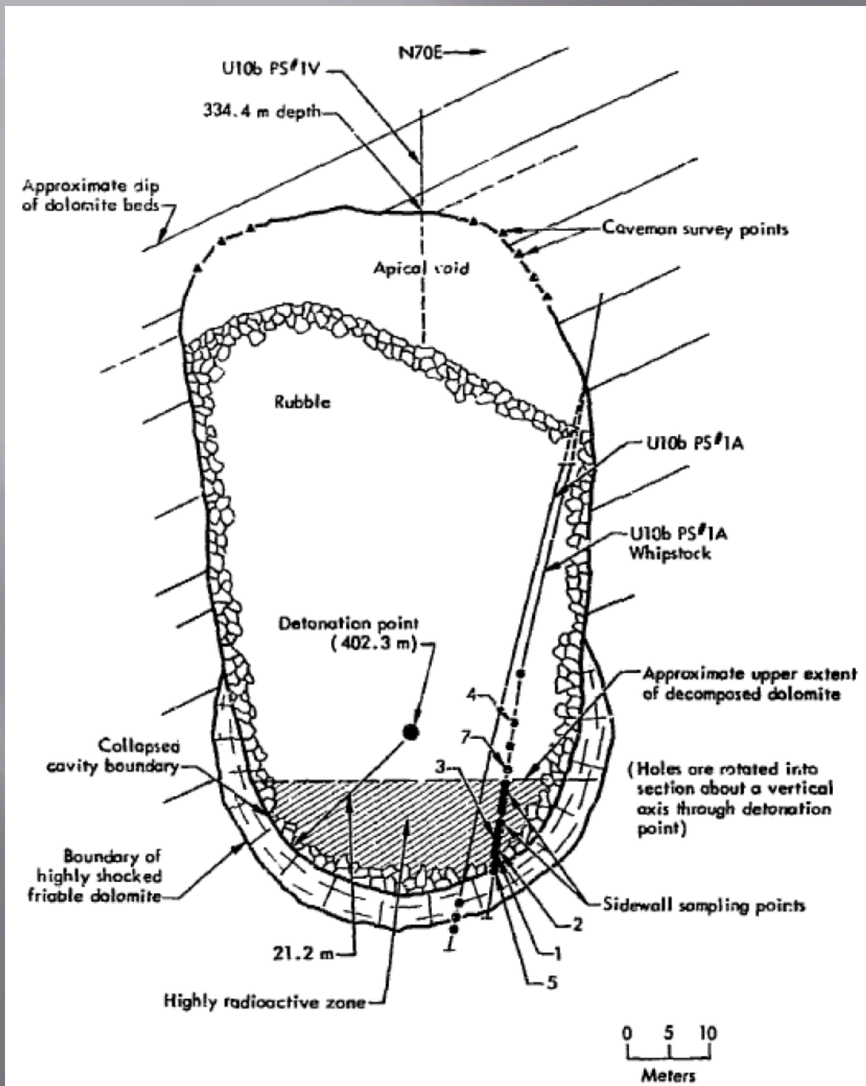


Microfractures as far as 300 ft from cavity.

Cavity 114 ft in diameter, floored by puddle of molten salt 32 ft deep.

December 3, 1966 – 0.4 kt Sterling test conducted in cavity.

Handcar test, November 4, 1964, 12 kt.
Plowshare Program. NTS.



Conducted to determine effects of nuclear detonation in carbonates (dolomite) and especially explosion-produced CO_2.

Result: dolomite, CO_2 little effect on chimney. Water content of host rock most important. But dolomite highly fractured, possibly reduced effect of CO_2.

Handcar chimney 1 yr after detonation.

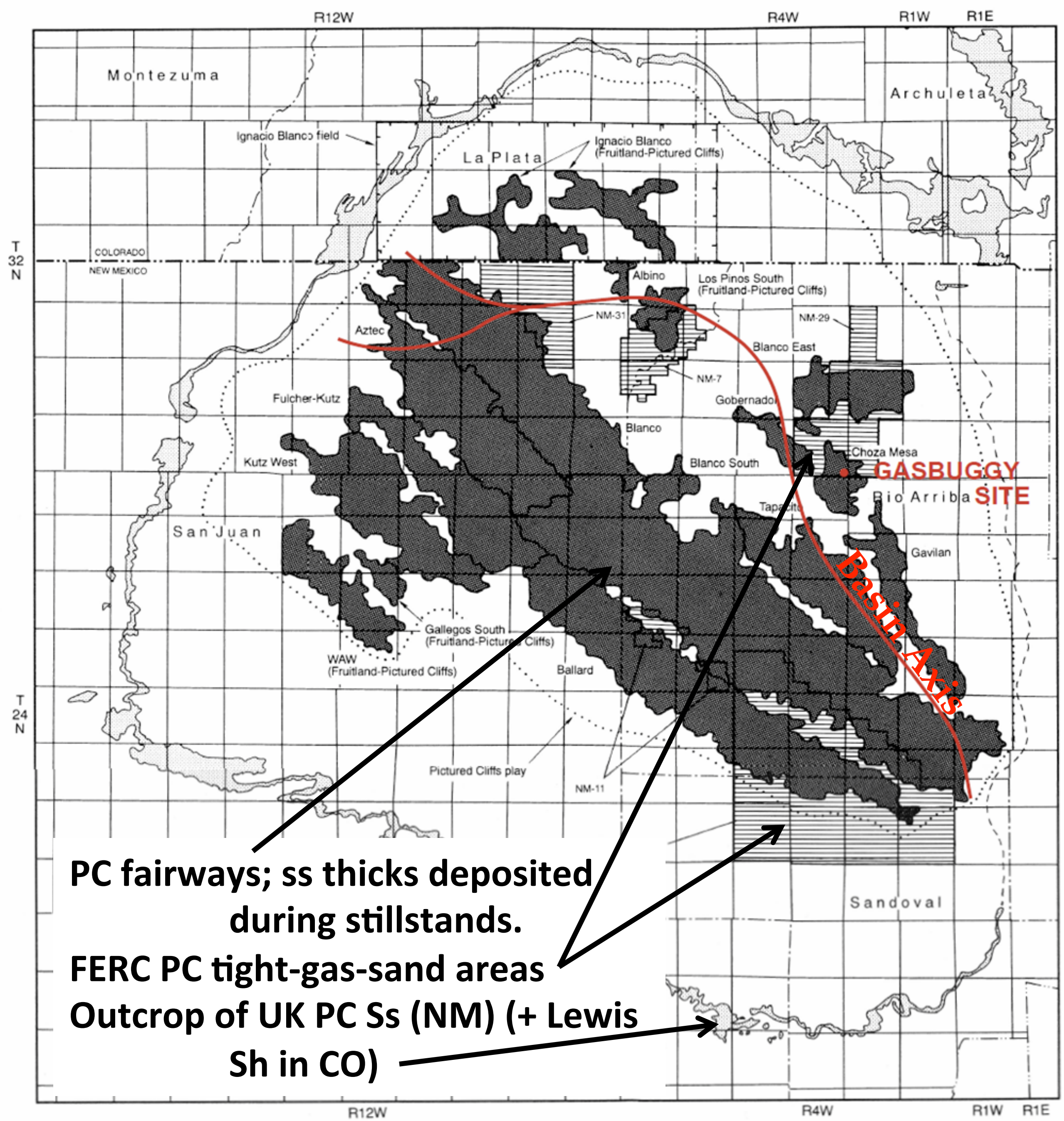
US Nuclear Frac'ing Tests: Gov't – Industry Partnership

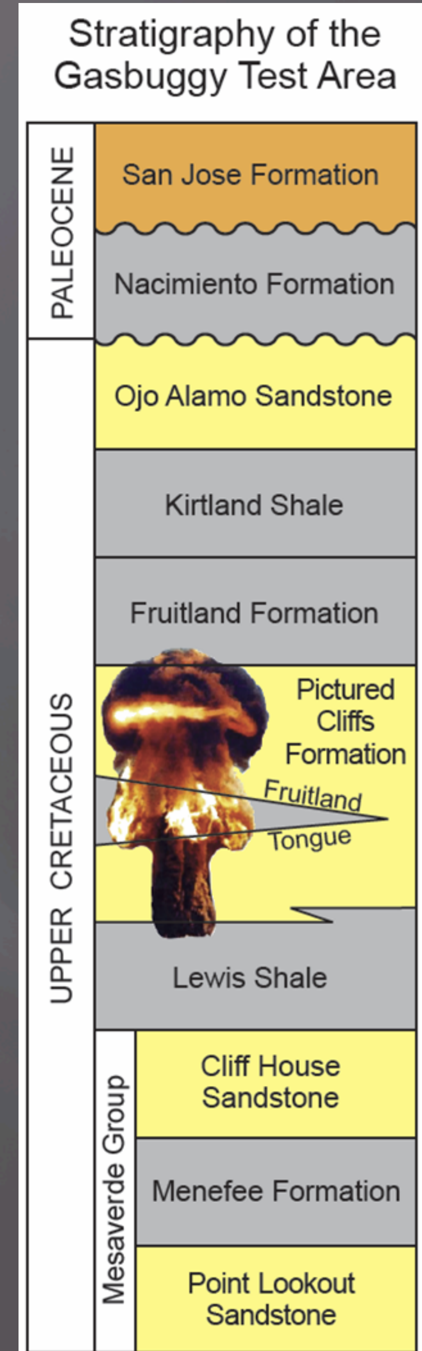
Gasbuggy (1967)
- US Atomic Energy Commission (AEC)
- US Bureau of Mines
- El Paso Natural Gas Company
- Lawrence Radiation Laboratory

Rulison (1969)
- AEC, USBM
- Austral Oil Company
- CER Geonuclear
- Los Alamos Scientific Laboratory

Rio Blanco (1973)
- AEC
- Equity Oil Company
- CER Geonuclear
- Lawrence – Livermore Laboratory

Background photo – Gasbuggy wellsite


R12W
R4W
R1W
R1E
Montezuma
Archuleta
Ignacio Blanco field
Ignacio Blanco (Fruitland-Pictured Cliffs)
La Plata
T 32 N
COLORADO
NEW MEXICO
Albino
Los Pinos South (Fruitland-Pictured Cliffs)
NM-31
NM-29
Aztec
Blanco East
NM-7
Gobernador
Fulcher-Kutz
Blanco
Kutz West
Blanco South
Choza Mesa
GASBUGGY SITE
Rio Arriba
Tapacito
San Juan
Gavilan
Basin Axis
Gallegos South (Fruitland-Pictured Cliffs)
WAW (Fruitland-Pictured Cliffs)
Ballard
T 24 N
Pictured Cliffs play
NM-11
Sandoval
PC fairways; ss thicks deposited during stillstands.
FERC PC tight-gas-sand areas
Outcrop of UK PC Ss (NM) (+ Lewis Sh in CO)
R12W
R4W
R1W
R1E


Stratigraphy of the Gasbuggy Test Area
PALEOCENE
San Jose Formation
Nacimiento Formation
UPPER CRETACEOUS
Ojo Alamo Sandstone
Kirtland Shale
Fruitland Formation
Pictured Cliffs Formation
Fruitland Tongue
Lewis Shale
Mesaverde Group
Cliff House Sandstone
Menefee Formation
Point Lookout Sandstone

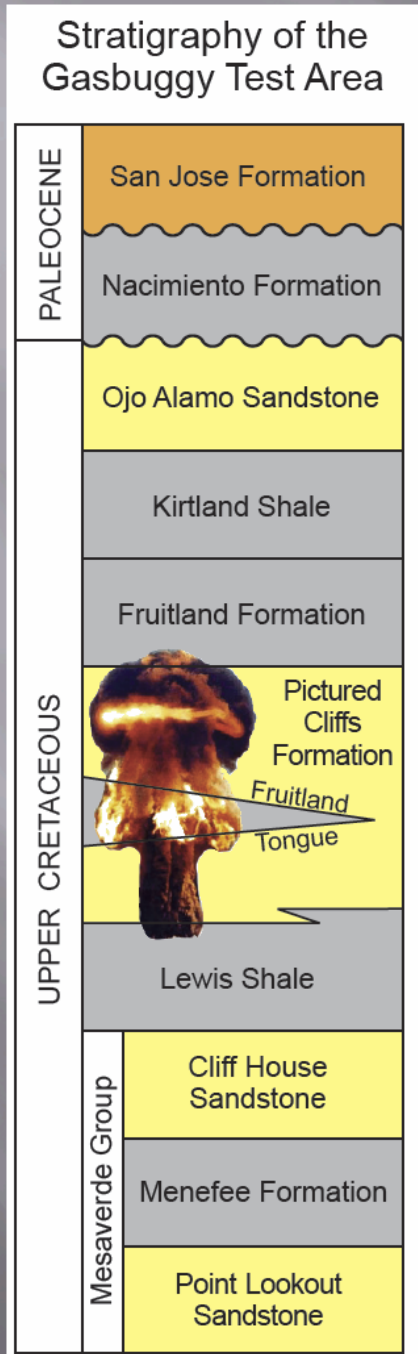
Pictured Cliffs Sandstone (Upper Cretaceous)

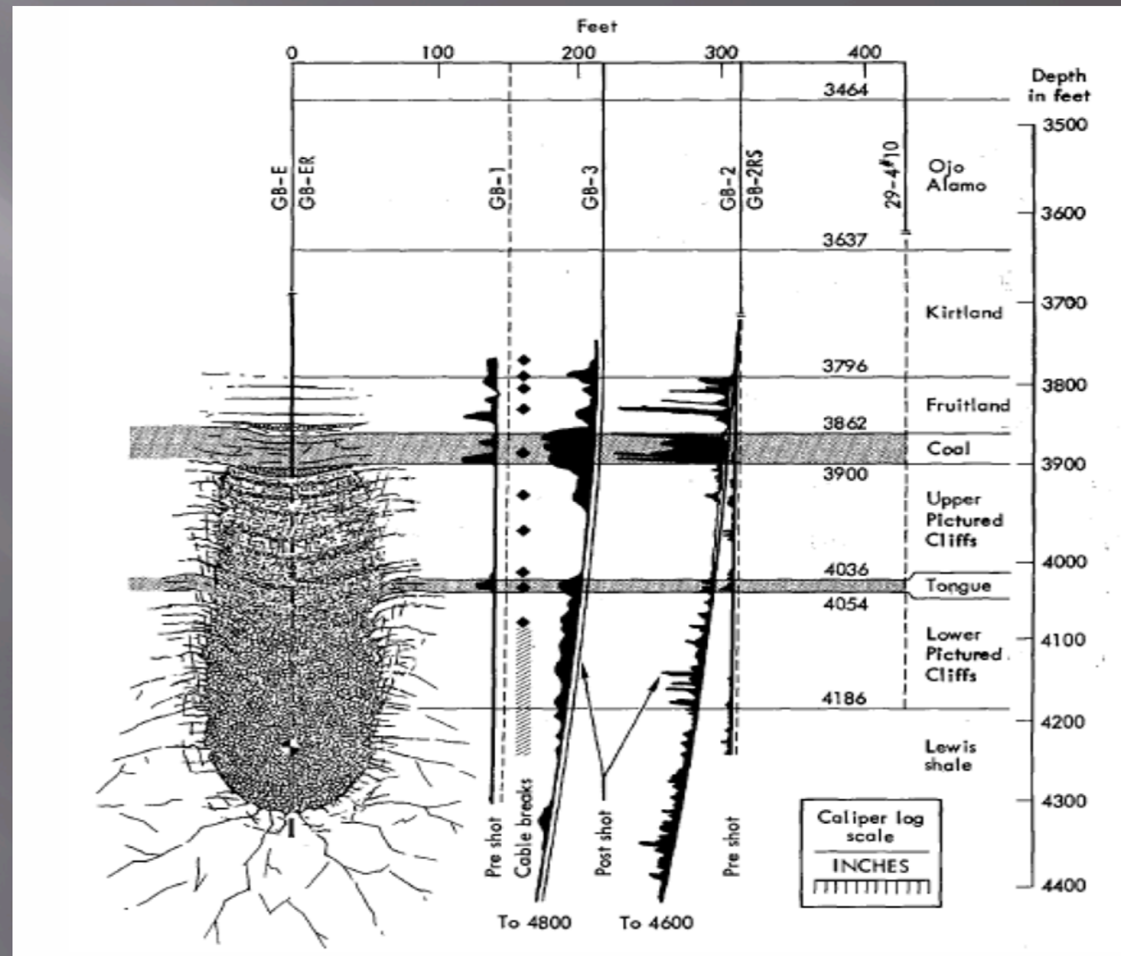
Avg. perm: 0.1 – 0.01 md
Calc. in-place reserves: 33 MMcf/ac, only 10% recovered by conventional wells
Calc. EUR by nuclear frac'ing: 67% at 160-ac spacing

Lowering Gasbuggy 29 kt fusion device into emplacement hole GB-E.

13 ft long, 18 in. in diameter. Detonated at depth of 4240 ft near top of Lewis Shale on December 10, 1967.

Gasbuggy Chimney





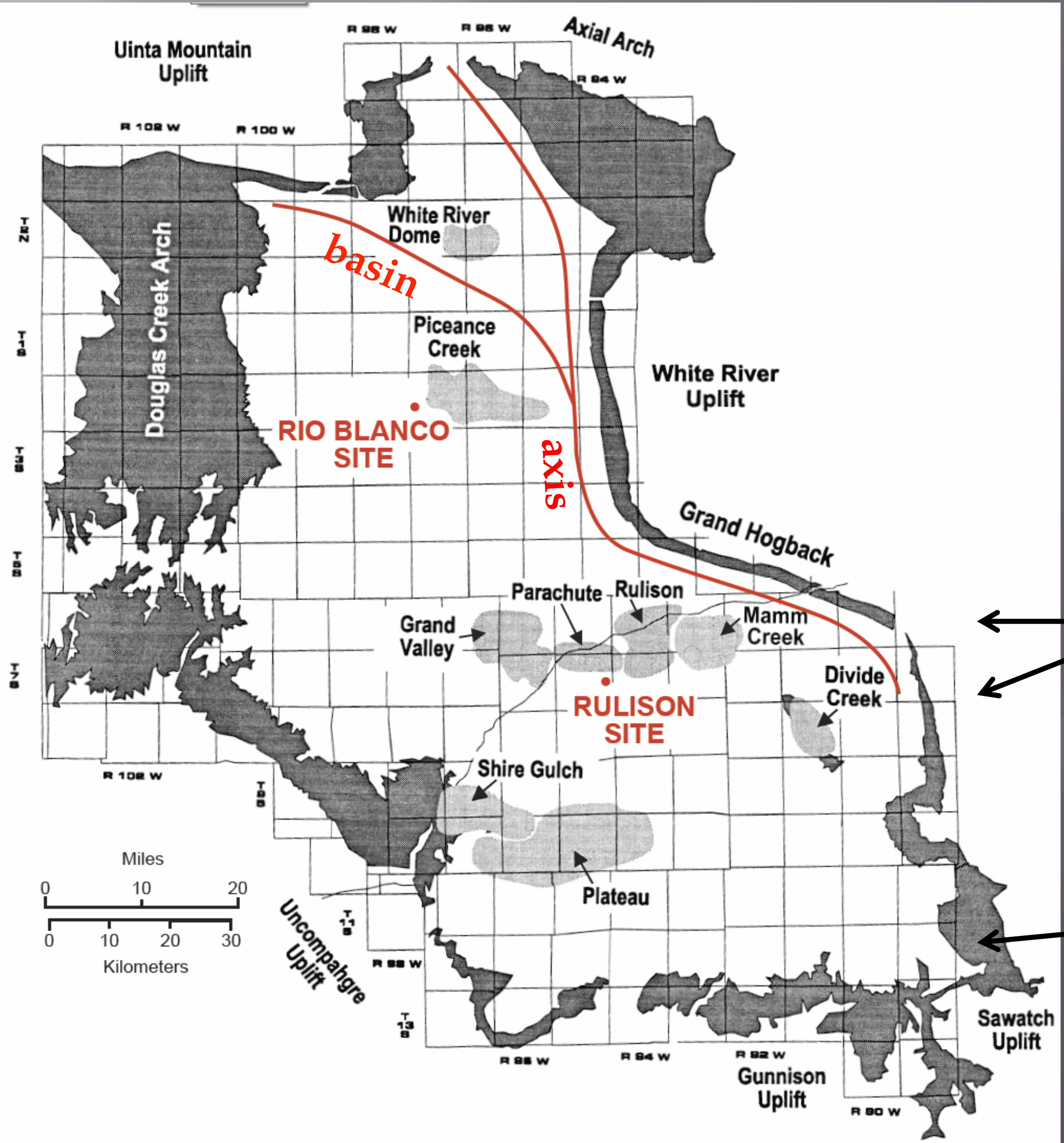
Shot point in Lewis Shale; fractures and cavity grew upwards into base of Fruitland Fm.

Goals and Results of Gasbuggy test:

1. Extent and character of shock-wave effects.
2. Change in productivity of nearby existing wells.
3. Radioactivity of produced gas.
4. Seismic effects.

1. Generated magnitude 4.5 +/- 0.3 to 5.2 earthquake.
2. Produced rubble-filled chimney 333 ft high, 160 ft diam.
3. Frac network 2.75X chimney radius
4. IP ~1mmcf/day; 2X to 7X that of nearby unstimulated conventional wells.
5. EUR ~1bcf/20 yrs; 8X that of local conv wells. <u>BUT</u>

6. High CO_2; some radionuclides in gas
7. Fractures not connected to chimney



Rulison and Rio Blanco sites, Piceance Basin, CO

major Mesaverde gas fields

outcrop of Mesaverde Group

Sketch SW-NE cross section, Piceance Basin and Rulison shotpoint

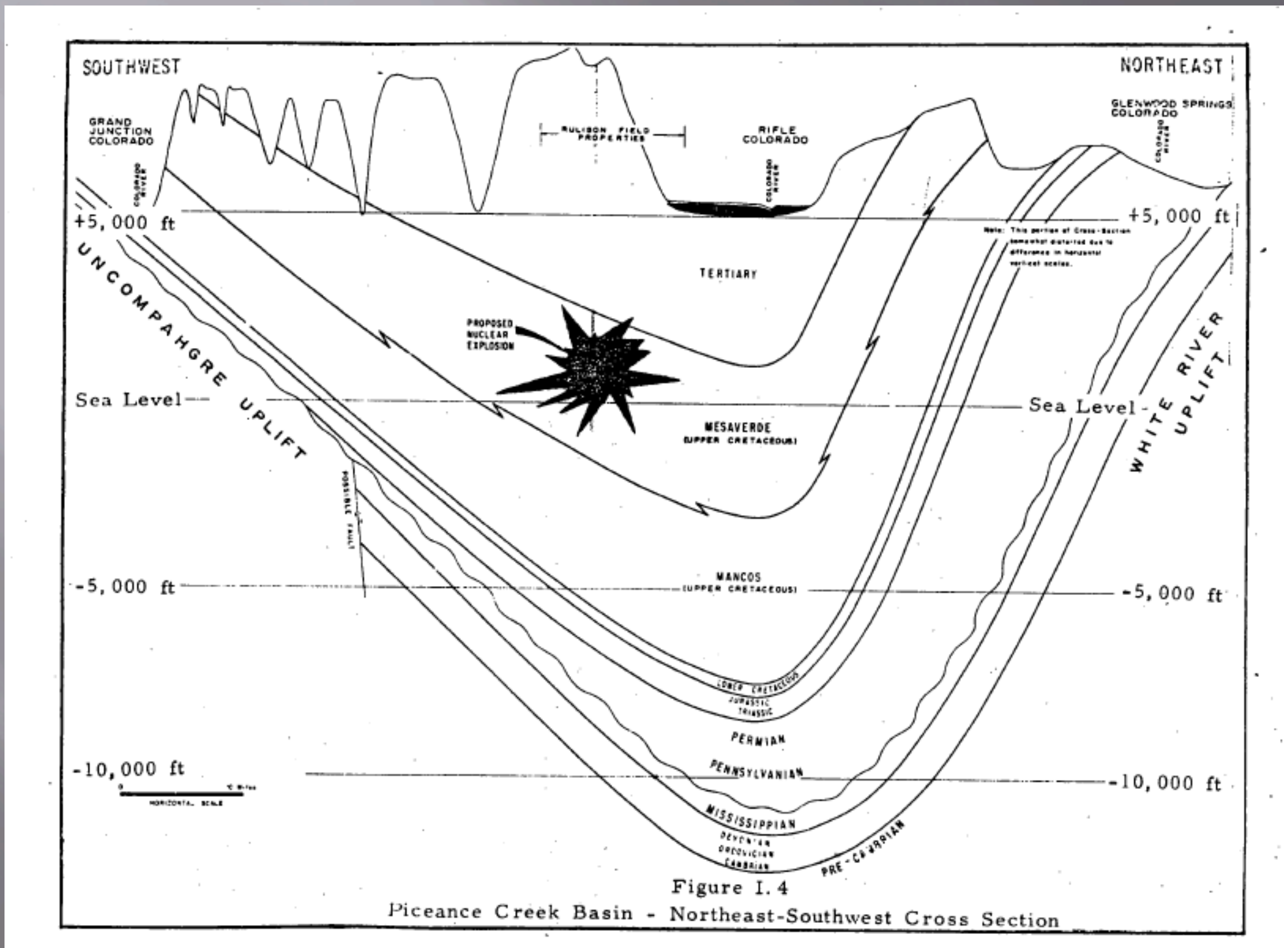
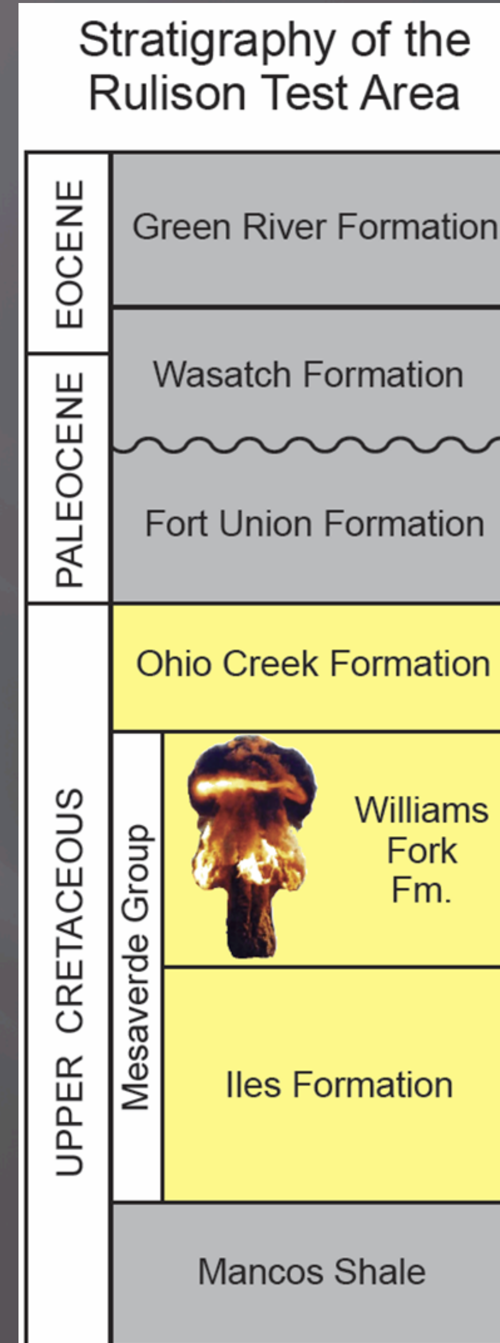
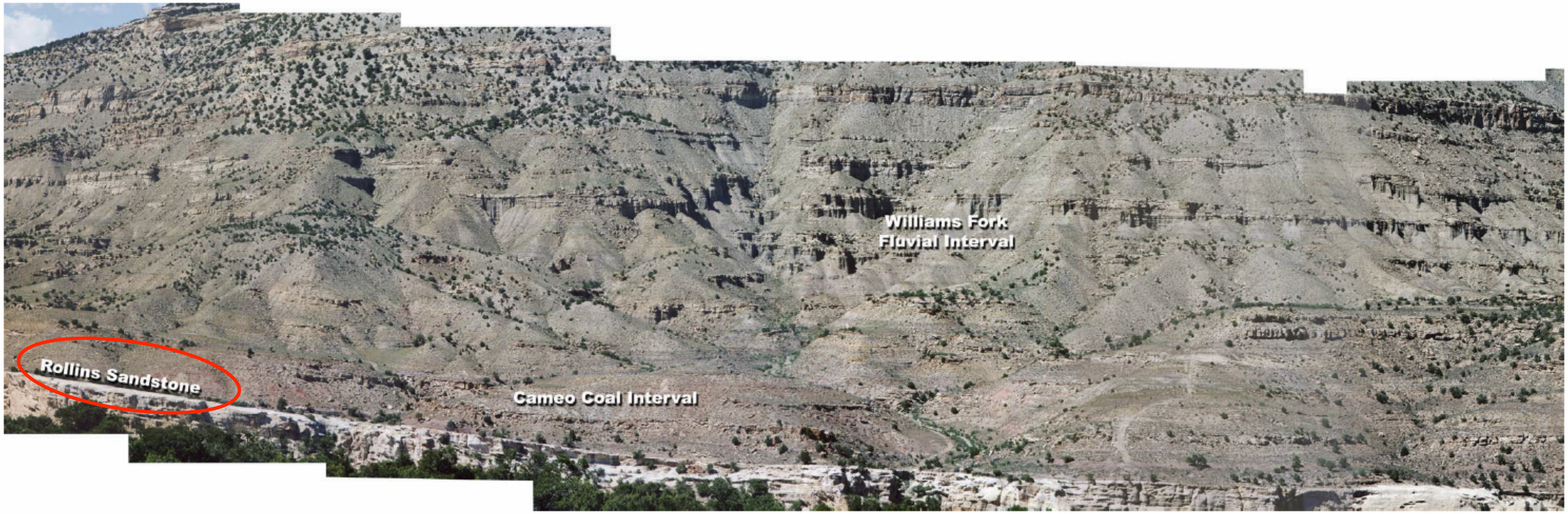
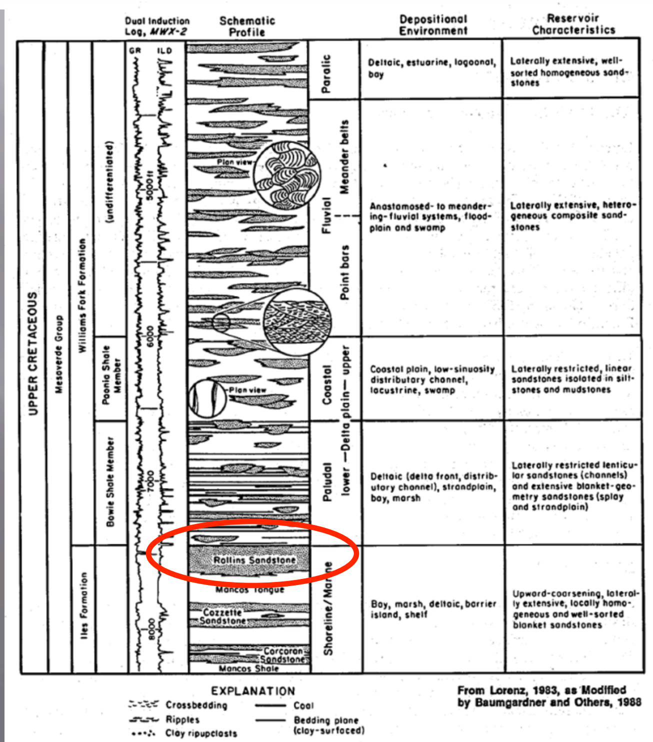


Figure I. 4
Piceance Creek Basin - Northeast-Southwest Cross Section

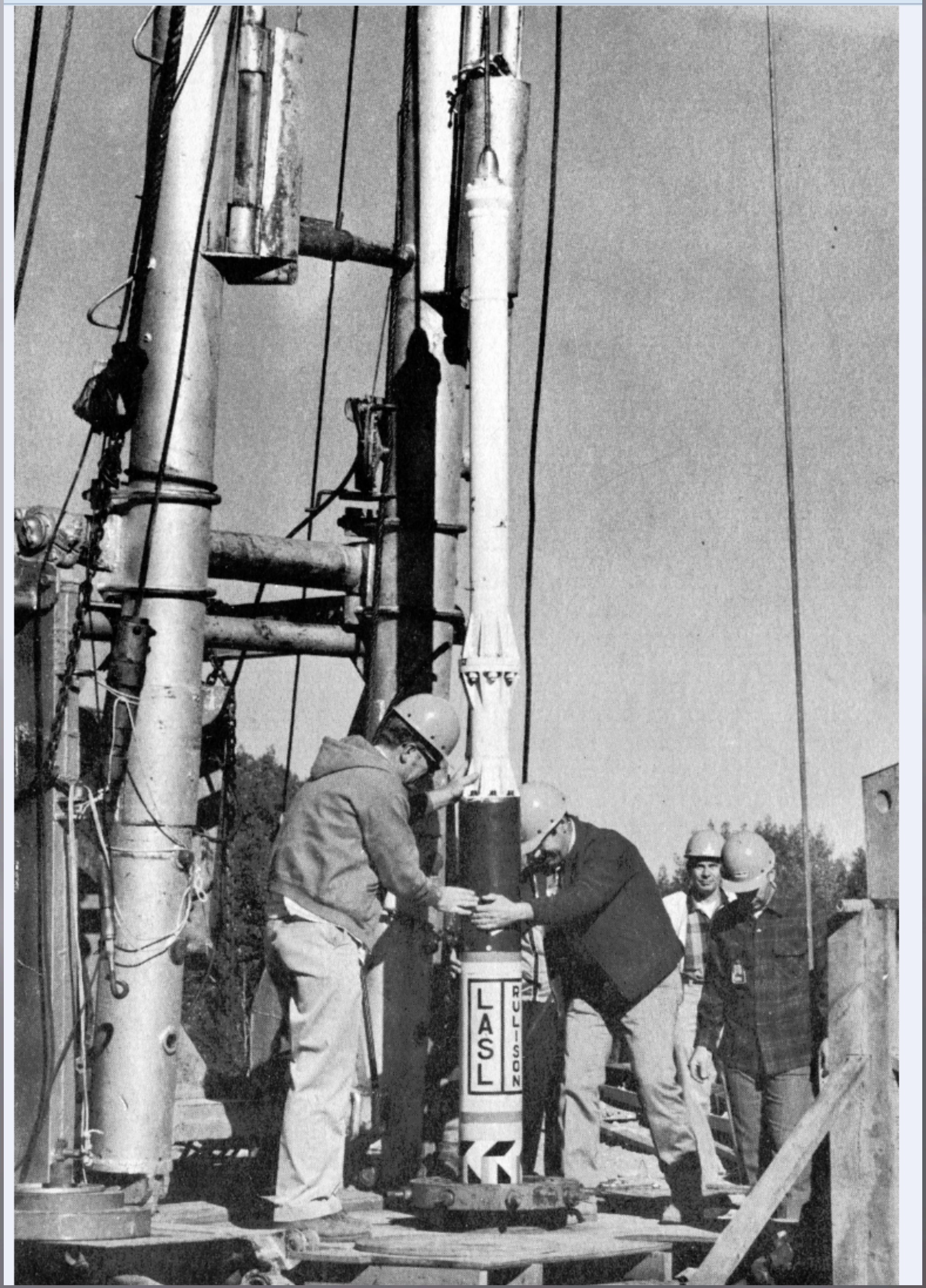






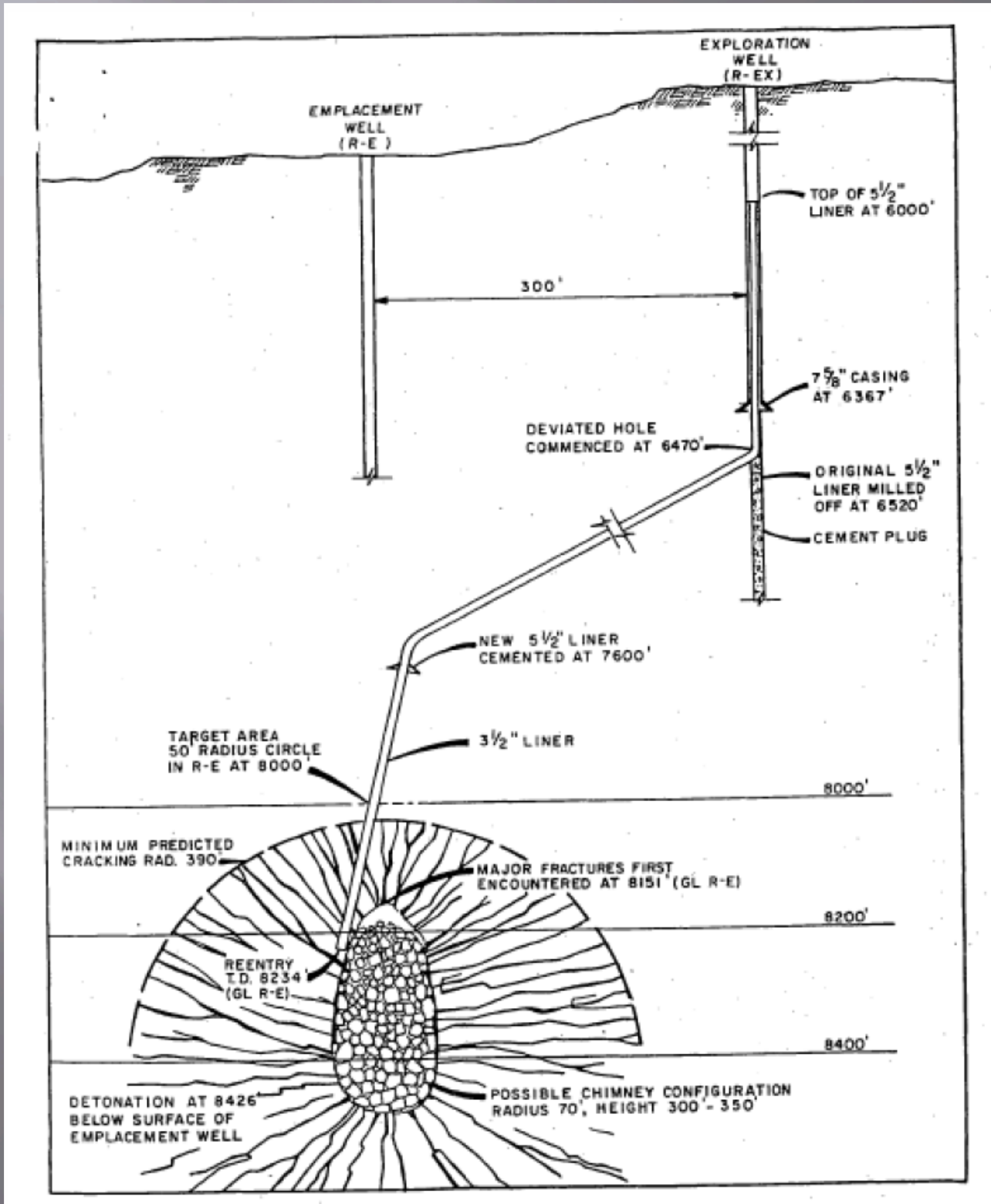
Photomosaic of Williams Fork Formation, Mesaverde Group, showing discontinuous nature of fluvial sandstones and fine-grained overbank deposits.

Note – Reservoir character very different from Pictured Cliffs Ss.



Lowering Rulison 43 kt fission device into emplacement hole R-E.

15 ft long, 9 in. in diameter, 1200 lbs. Detonated at depth of 8426 ft in Mesaverde Group on September 10, 1969.



Sketch of Rulison chimney showing emplacement well R-E, pre-shot exploration well R-EX, and post-shot R-EX redrill.

Goals and Results of Rulison test:

1. Goals similar to Gasbuggy – potential to fracture-stimulate tight gas sands; increase perm of fracture zone; minimize radionuclides in gas; measure seismic effects.

1. Caused M 5.4 earthquake and 16 <M 1 aftershocks in first 43 minutes after shot.
2. Geophones detected collapse from 4.8 to 150 secs after shot, some noise for next 9 hrs.
3. Produced chimney 350 ft high, 152 ft in diam.
4. Fracture network 3X to 5X chimney radius (designed 6.5X)
5. 108-day prod test ~0.5 bcf; 2X to 4X that nearby conv wells
6. EUR ~1.8 bcf/20 yrs; 2X to 3X that of local wells. BUT

7. High CO_2, water vapor, some radionuclides in gas
8. Public concern

January 1, 1970 (Back to Context)
National Environmental Policy Act of 1969

Required all federal government agencies to prepare environmental assessments and issue environmental impact statements.

Established the President's Council on Environmental Quality that eventually became the Environmental Protection Agency (EPA).

Effect on Plowshare: NEPA could not force release of nuclear technical data, but could force public disclosure of on-site and off-site consequences of detonations.

Schedule for Construction of Nuclear Stimulated Gas Wells (Rio Blanco Environmental Impact Statement, US Atomic Energy Commission, 1973)

TABLE 1

SCHEDULE FOR CONSTRUCTION OF NUCLEAR STIMULATED GAS WELLS

Construction Region	Area, Sq.Mi.	1973	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	Add'l Time to Complete Field Dev., Years	Approx. Year of Field Completion	Total Wells
Green River (N)	600			WW			5 WWII	5	10	20	30	35	35	35	35	35	35	→ ~28 →	2016	120[illegible]
Green River (S)	540					EXP			5	5	10	20	30	35	35	35	35	→ ~26 →	2014	108[illegible]
Piceance (N)	550	RB			5 RBII	---	10	20	30	35	35	35	35	35	35	35	35	→ ~22 →	2010	110[illegible]
Piceance (S)	650					5 RuII	---	10	20	30	35	35	35	35	35	35	35	→ ~29 →	2017	130[illegible]
Uinta (1)	300						EXP			5	5	10	20	30	35	35	35	→ ~13 →	2001	600
Uinta (2)	200								EXP			5	5	10	20	30	35	→ ~ 8 →	1996	38[illegible]
TOTAL PRODUCTION WELLS					5	5	15	35	65	95	115	140	160	170	195	205	210	210 210		5665

* Assuming 2 wells per section

WW = Wagon Wheel

RB = Rio Blanco

Ru = Rulison

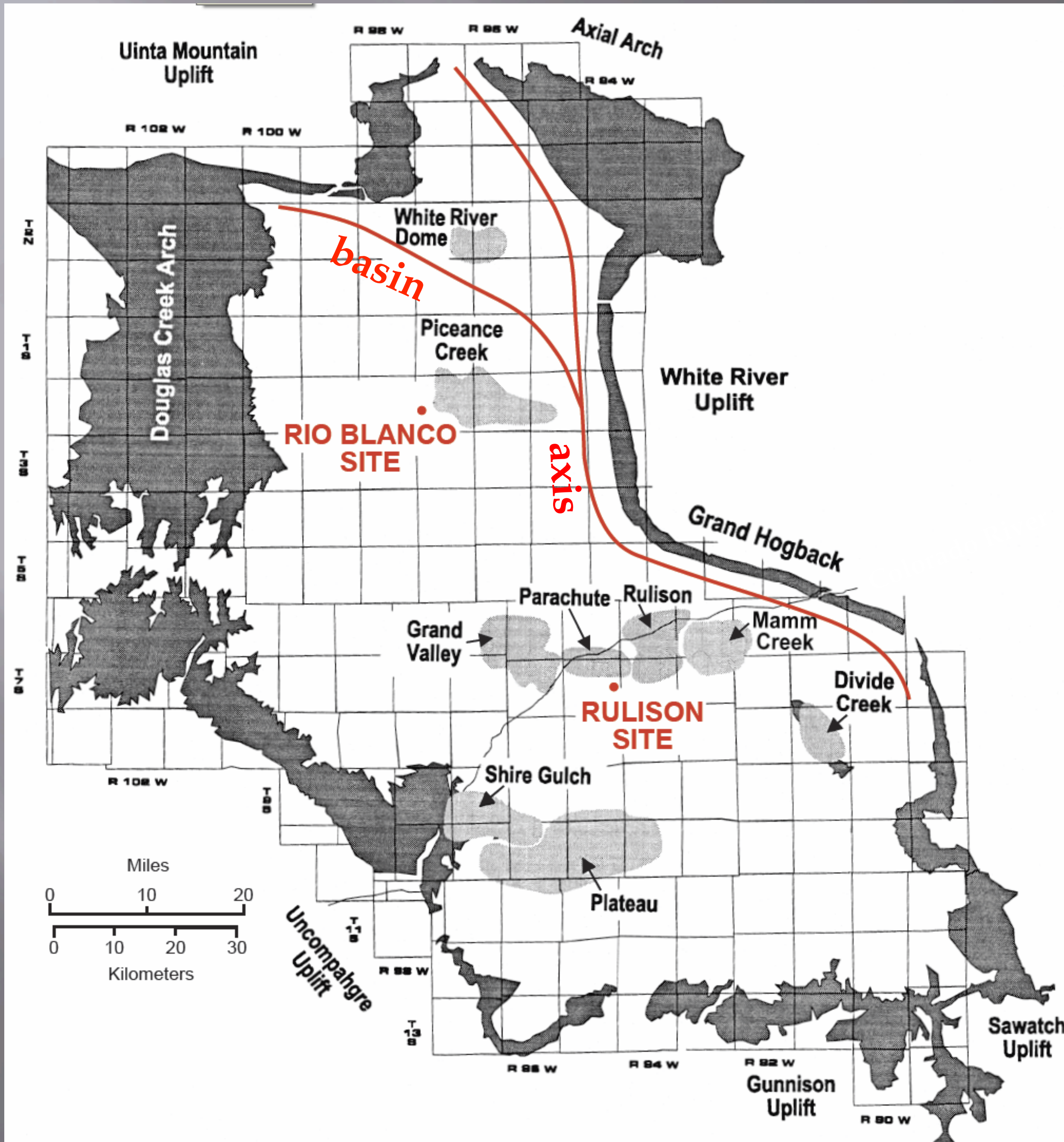
EXP = Experimental Well

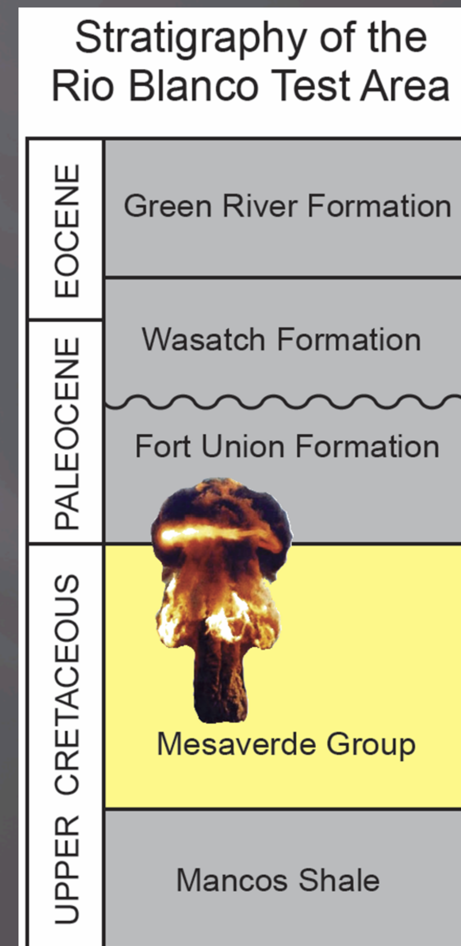
NOTE: Year of table entry is shot year
Emplacement well drilling occurs in previous year
Gas production begins in following year

- 7 -

5665 wells in Green River, Piceance, and Uinta Basins, finished in 2017. At 3 to 5 devices/well, 17,000 to 28,000 nuclear devices would be required.

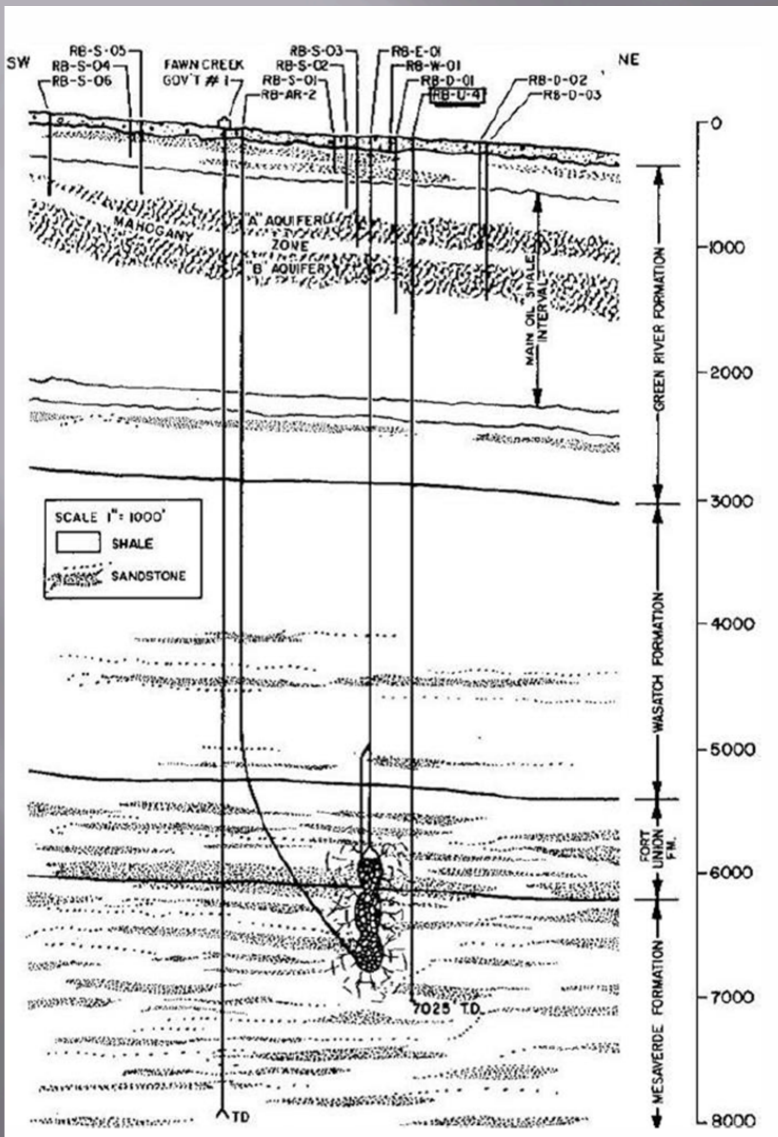
Rulison and Rio Blanco sites, Piceance Basin, CO





Rio Blanco rig and device; One of three 33-kt nuclear devices being lowered into emplacement hole RB-E-01.

3 simultaneous 33-kt shots
May 17, 1973



Results:

1. M 5.4 earthquake, rock-falls, 95 aftershocks (max M 2.5) to 8 days after shot
2. IP 5.5 mmcf/day for 7 days but rapid pressure drop

<u>BUT</u>

3. Chimneys not connected
4. Upper chimney production much less than predicted
5. Amount of induced micro-fracturing very small
6. CO_2, ^{85}Kr in gas, tritium in gas and steam
7. Large public outcry

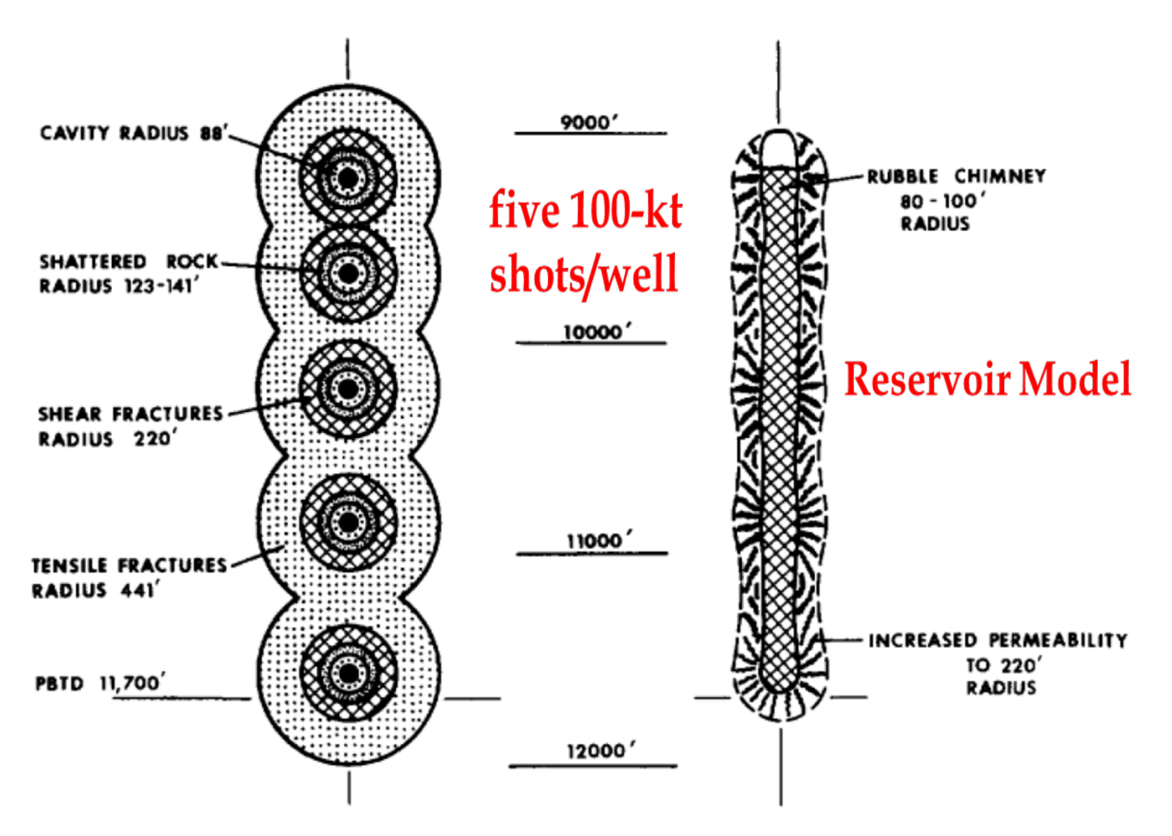
Summary of Rio Blanco Test:

"…… More bluntly stated – if we had known in 1972 what we know now about this site, this project would not have been executed there." (Ballou, 1976, Lawrence Livermore Laboratory report)

Despite this statement about having chosen a poor site, Rio Blanco marked the last attempt to nuclear-fracture-stimulate a gas well in the U.S.

And no other tests were ever conducted in a Pictured Cliffs-type reservoir or a carbonate reservoir.

Proposed, post-Rio Blanco tests: Wagon Wheel and Wasp.



Wagon Wheel – five sequential* 100-kt shots into UK and PEo strata in Pinedale Field, Green River Basin to produce 2700-ft-high chimney and envelope of induced fractures.

Wasp – 50-kt shot, 11,000 to 12,000 ft deep on Pinedale Anticline, same strata as Wagon Wheel. Abandoned.

* Limited by July 1974 Threshold Test Ban Treaty

The Demise of Plowshare

A Technical Success; an Economic, Political, and Social Failure

- Excavation. Fallout from Sedan, Limited Test Ban Treaty
- First Plowshare test (Gnome) – Geyser of radioactive steam, smoke (inauspicious beginning)
- Gasbuggy, Rulison, Rio Blanco
    - CO_2, ^{85}Kr, tritium in gas
    - Production, fractures less than predicted
- Growing environmental movement
    - NEPA and required Environmental Impact Statements
    - Opponents organized, support muted
    - No government protection against liability
    - Cold War fear of nuclear explosives
- September 1975 – Plowshare terminated. $82M spent.

THEN AND NOW

- HOW REAL?

- HOW IMPORTANT AS DRIVERS OF ACCEPTANCE OF NEW TECHOLOGY?

- Anti-Nuclear Sentiment ⟷ Climate-Change Concern

- Radioactive Gas ⟷ Groundwater Contamination

- Viet Nam War / Watergate, Distrust of Government ⟷ BP Macondo, Keystone, Distrust of Big Oil

Anti-Nuclear Sentiment – Climate-Change Concern

- Both real in the Public's eye.
- Fear (vs. Facts) drove/driving Public Opinion.

Some questions for which I have no answers:

Would public have accepted nuclear frac'ing if Cold War mentality didn't exist?

Would public accept hydraulic frac'ing if climate change wasn't a concern?

Yes, but still have G/W contamination issue (next slide)

No, but gas (bridge to future) >>> oil >>> coal

Radioactive Gas ⟷ Groundwater Contamination

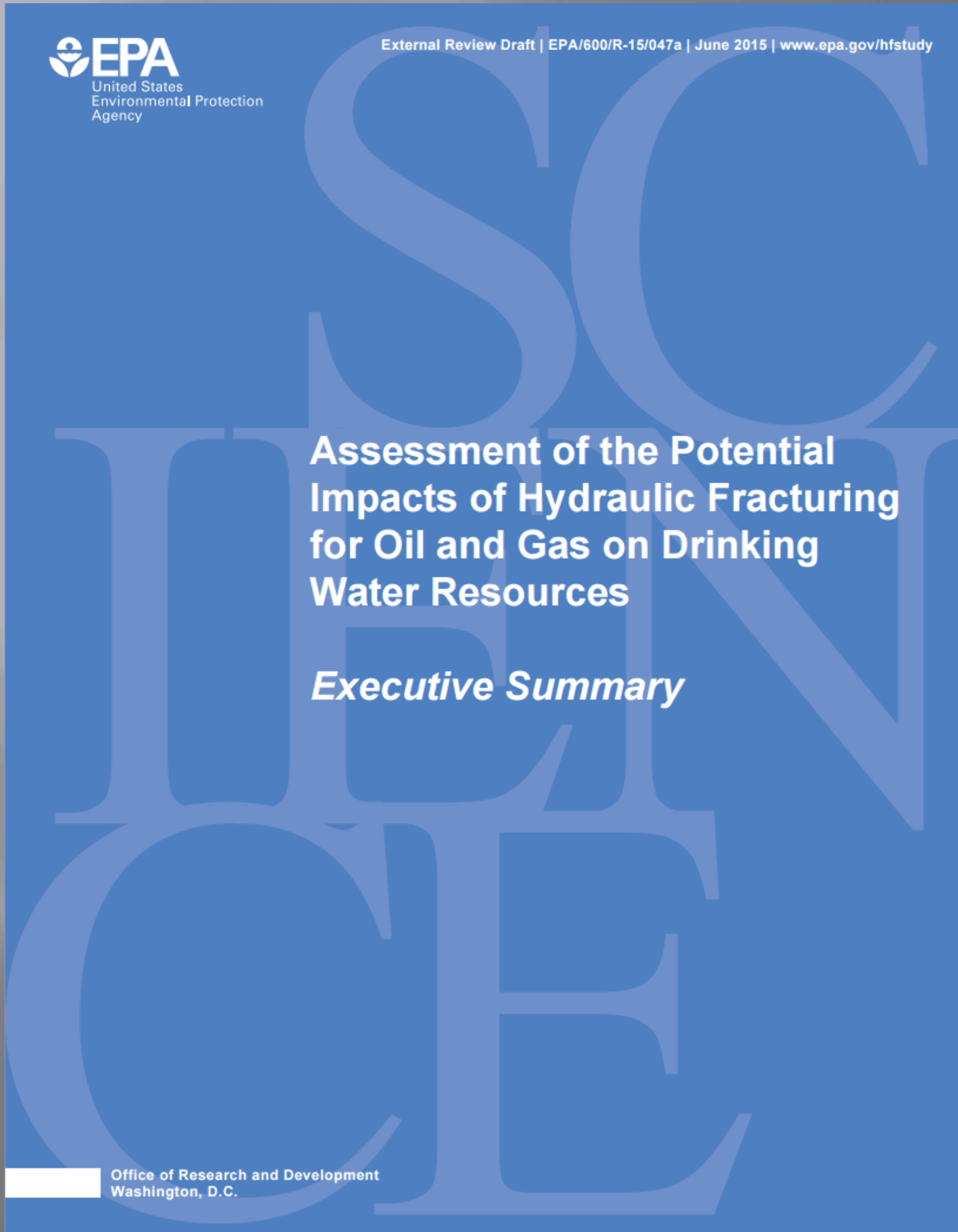
- Hazards: ^{85}Kr, ^{14}C (very low), tritium
- Solutions:

  Device – fission <<< fusion (tritium)
  shielding

  Gas Production – dilute*, delay, generate in remote areas*

  Tritiated Water – store, ship, re-inject

* Modelling suggests <0.64 to <1.0 mrem/yr for mixing model and <0.11 to <2.1 mrem/yr for power-generation model vs. ~100 mrem/yr natural background



"The number of identified cases where drinking water resources were impacted are small relative to the number of hydraulically fractured wells."

So ……….

Fear of radioactive gas, fear of contaminated groundwater overblown?

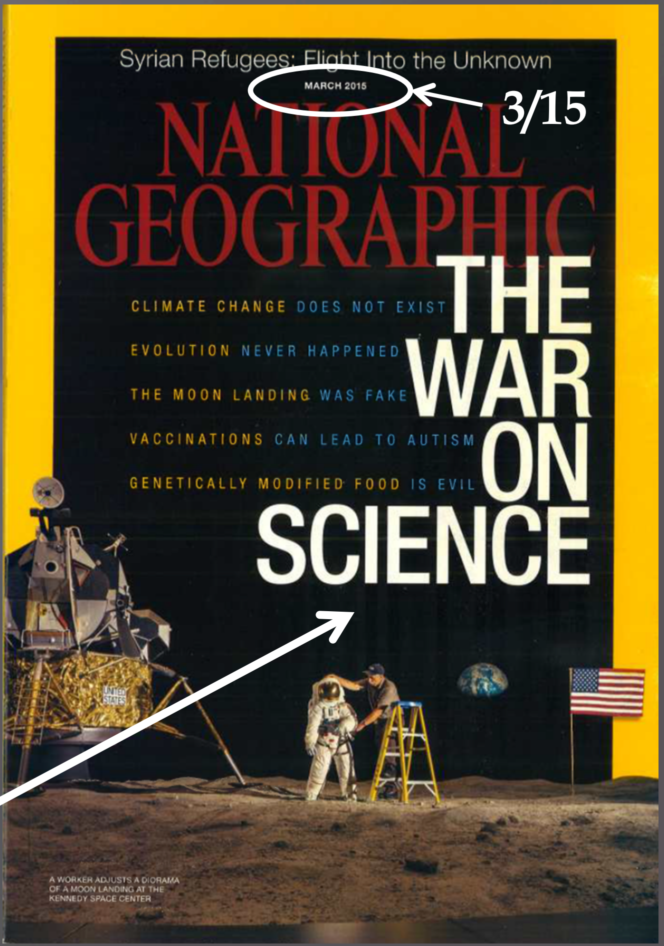
(Knee-jerk?) Distrust of Government – Big Oil

Then – Were the most qualified industry people scared off leaving only gov't scientists? Who was Austral Oil Company? Equity Oil Company? Why no Exxon, Texaco, Chevron, Mobil?

Now – Are geologists/ engineers with environmental backgrounds being ignored by industry?

WHAT TO DO?

- Geoscientist recognition/acceptance of public concern (nuclear explosions or climate change) whether valid or not
- Fully educate the public about the process and
- Full disclosure of potential for harm (radioactive by-products or frac fluids)
- Enlist non-Big Oil support for process. (Note: 2015 EPA report)
- Acknowledge process not 100% safe; accept responsibility for accidents; strive to make process safer
- Financially protect public from all (including long-term) consequences



BUT (a new issue)

THANK YOU