GEOLOGY OF PROJECT WAGON WHEEL NUCLEAR STIMULATION PROJECT

Jack Shaughnessy
R.H. Butcher
El Paso Natural Gas Company
Farmington, New Mexico

ABSTRACT

Wagon Wheel is a project planned to stimulate gas reservoirs of the Pinedale Anticline by means of nuclear explosives. The Pinedale Field, located in the northern portion of the Green River basin of southwest Wyoming, is potentially productive from nearly 10,000 feet of lower Fort Union, Lance-Lewis, and Mesaverde equivalent sandstones. Attempts to produce the field conventionally have proved uneconomical due to low permeability.

The first nuclear stimulation experiment was Gasbuggy, in northwest New Mexico, detonated in 1967 using a 29 kiloton explosive. Technical questions answered by Gasbuggy resulted in the program at Wagon Wheel, which is an actual attempt at economic use of nuclear energy.

Wagon Wheel No. 1 was drilled to 19,000 feet to evaluate the entire Mesaverde section. Gas was detected on mud logging equipment throughout the basal Fort Union, Lance-Lewis and Mesaverde, below the top of the gas reservoir at 7,972 feet. The well has been plugged back to 11,700 feet as a possible emplacement hole in which five 100 kiloton explosives will produce a chimney from 9,000 to 11,650 feet. Reserves in this interval are calculated at 207 billion cubic feet of gas in place per square mile.

Extensive logging, coring and testing have been carried out in the program, including special logs for rock mechanics study. Cores were compared to Gasbuggy with regard to rock strength, shear behavior and potential fracture formation.

Two special wells in addition to the Wagon Wheel No. 1 were drilled for the primary purpose of evaluating the aquifers above the gas reservoir. Potable water extends to a depth of 3,730 feet. Salt water occurs from 3,730 to 5,630 feet. Low quality subpotable water extends from 5,630 to 7,140 feet. The salt water zone is interpreted to be a tongue of Wasatch extending from the west into Eocene arkoses derived from the Wind River Range to the east.

Plans call for sequential detonation of five explosives spaced at intervals from 9,220 to 11,570 feet, to produce a more or less continuous chimney from 9,000 to 11,650 feet. There will be a safety margin of 1,600 feet between the top of fractures and the bottom of the known aquifers.

The geological profession has long been aware of the decrease in exploration for new reserves of oil and gas throughout the United States during the last decade. This decrease has resulted in the current shortage and a possible depletion of reserves in the next 15 years. Numerous methods have been suggested to alleviate this crisis including nuclear stimulation of gas reservoirs. The Atomic Energy Commission (AEC) and private enterprise are currently experimenting with nuclear energy to stimulate low permeability gas reservoirs common to parts of the Rocky Mountain Region. El Paso Natural Gas Company is presently working on its second test, known as Project Wagon Wheel. The first test, Project Gasbuggy, was conducted in the San Juan basin expressly as a technical experiment (fig. 1). Information gained at Gasbuggy helped lead to the present test of the Pinedale Unit located in western Wyoming, 20 miles south of the town of Pinedale.

One other test using nuclear energy was undertaken by Austral Oil Company at Project Rulison in Colorado. Another test, Project Rio Blanco, is currently in the planning stages by the Equity Oil Company and CER Geonuclear.

Gasbuggy utilized a device of 29 kilotons, Rulison was approximately 40 kilotons, Rio Blanco is planned as a multishot fired simultaneously and Project Wagon Wheel is programmed as five separate explosives, each of approximately 100 kilotons, fired sequentially. At this time, the AEC is designing and testing hardware to be used for the sequential-type of firing technique. The earliest date for the detonation of Wagon Wheel is estimated for the fall of 1974. In addition, AEC has developed a new class of nuclear explosives designed specifically for gas stimulation to reduce the level of tritium.

The Pinedale Unit, located in the northern portion of the Green River basin, covers an anticline thirty miles long and five to six miles wide situated between the Wind River Mountains, a Precambrian complex, and the Big Piney-LaBarge Platform (fig. 2). The Rock Springs Uplift lies about 65 miles to the southeast. Approximately 90,000 acres are located within the unit boundary encompassing an area of over 200

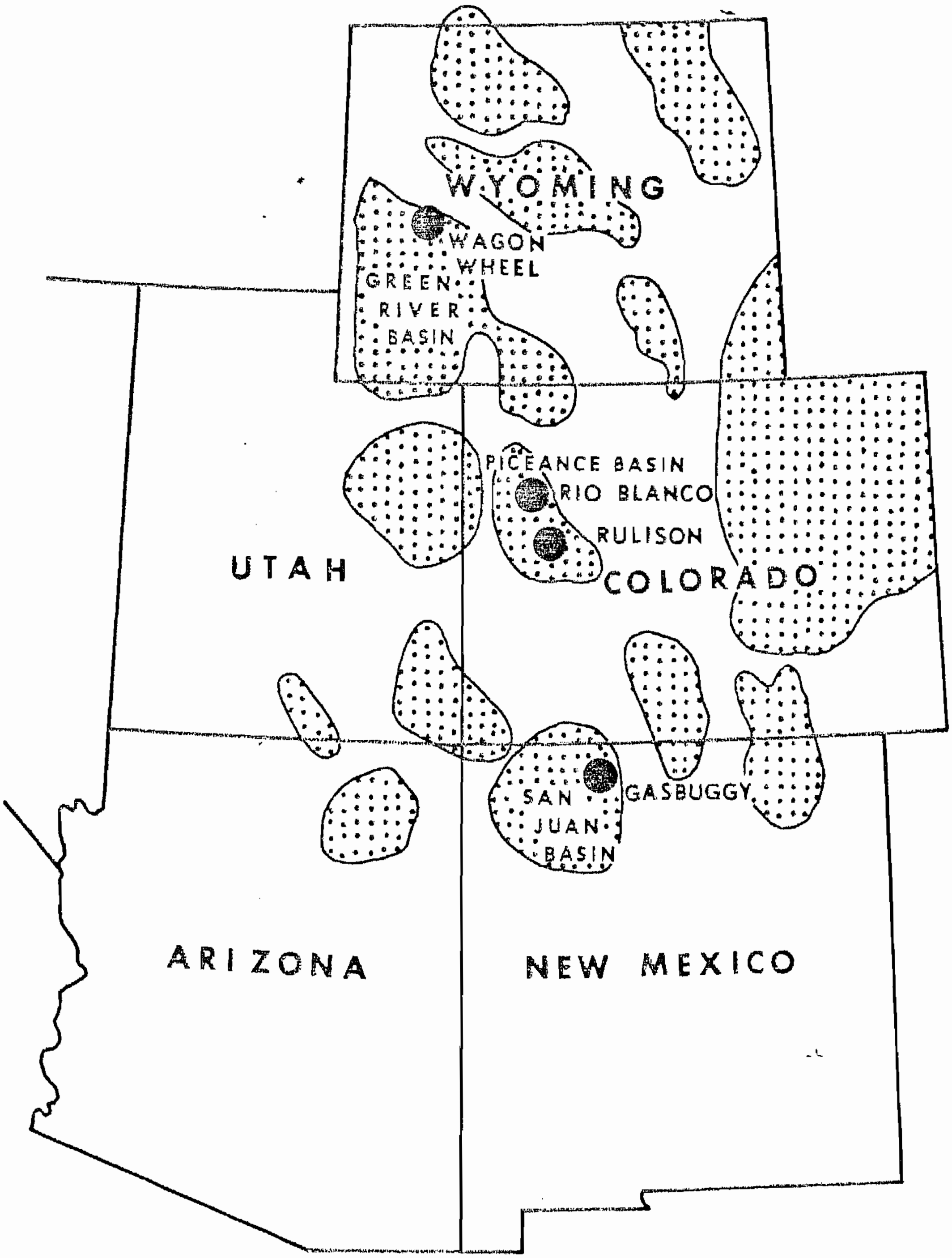


Fig. 1 Index map of Nuclear Stimulation Projects located in the Rocky Mountains.

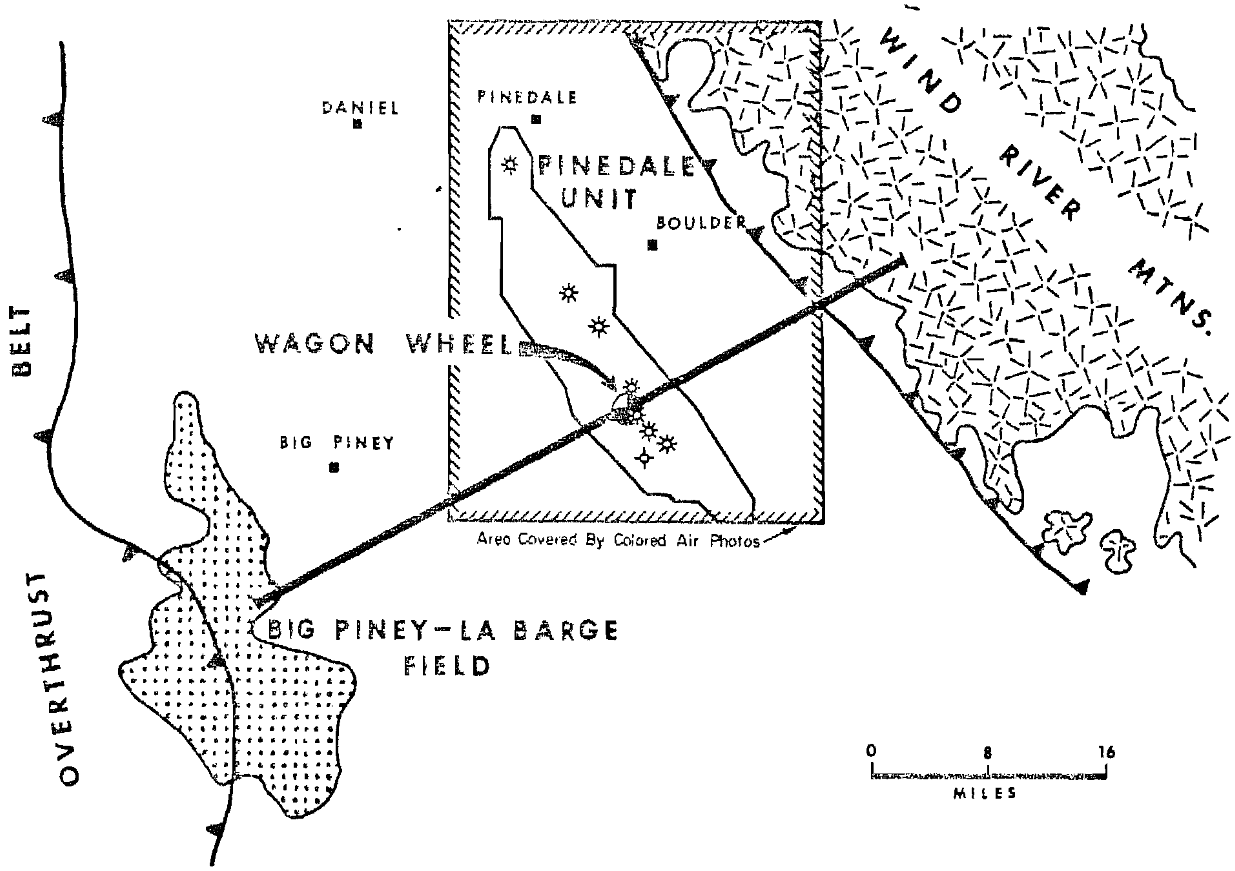


Fig. 2 Index map of the northern Green River Basin showing location of cross section, area covered by colored aerial photographs and the outline of the Pinedale Unit.

square miles within Townships 29 through 33 North and Ranges 107 to 110 West.

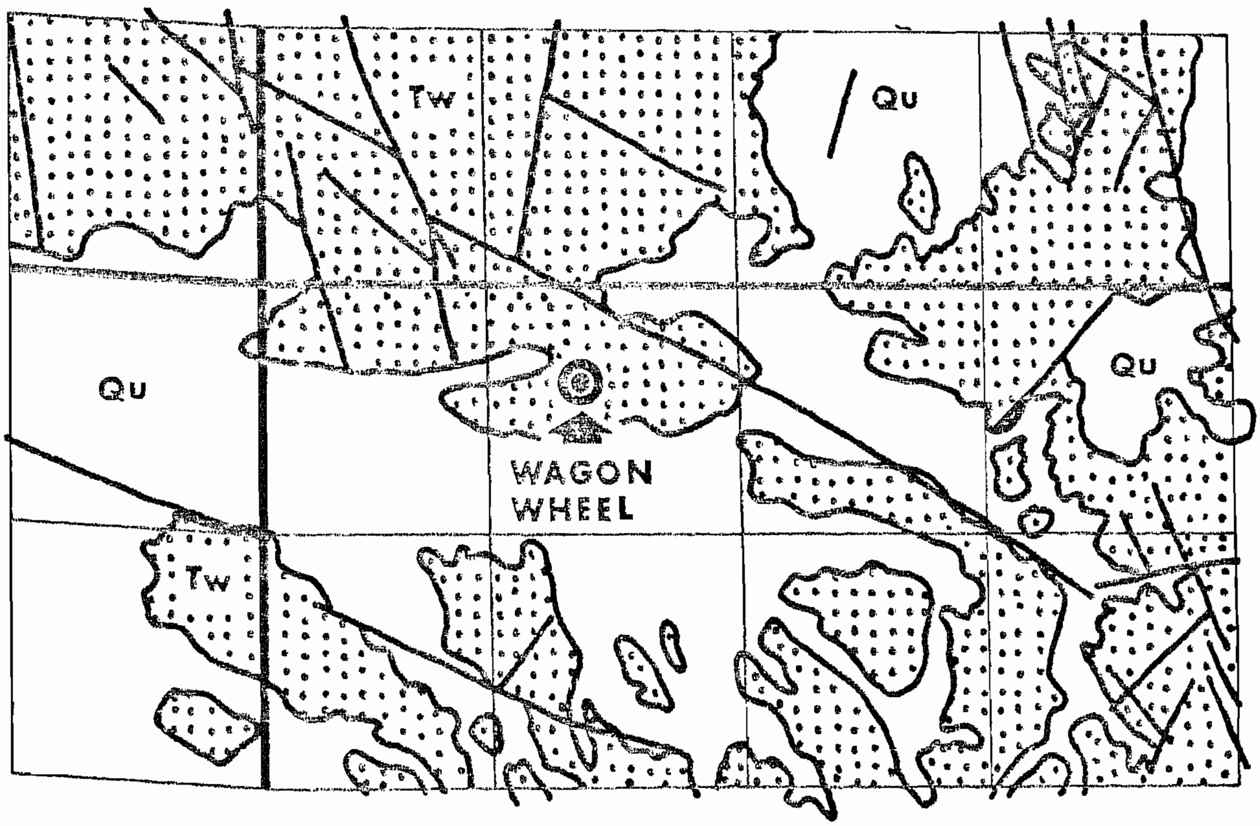
To define the surface and subsurface structural geology to the AEC, El Paso contracted services for colored aerial photography studies within the area outlined in figure 2 and seismograph surveys parallel and perpendicular to the axis of the anticline. Color photography was used to accentuate the subtle hues of the low dipping Wasatch strata which revealed the presence of photo lineaments. The lineaments were interpreted to be fractures and/or faults even though field checks conducted immediately surrounding the Wagon Wheel location failed to confirm their presence (fig. 3). The important question to be answered from this interpretation was that assuming the fractures and/or faults exist, do they provide an avenue of communication between the groundwater aquifers and the gas-bearing reservoirs? Hydrological tests and drill-stem test data indicate that the aquifers are independent of each other as all displayed significantly different static levels. Furthermore, communication does not exist between the gas and the groundwater reservoirs. The study identified a thick sequence of fresh water aquifers with normal hydrostatic pressures to a depth of 3,730 feet. Gas pressures above normal hydrostatic are present in the reservoirs below the depth of 7,972 feet.

The seismic profiles were interpreted to show a reverse fault with approximately 600 feet of vertical displacement located west of the Pinedale Anticline. If this fault were projected to the surface, it would be approximately 2½ miles west of the Wagon Wheel location. As the fault is traced downward, it curves towards the Wind River Mountains and intersects the Wagon Wheel borehole at a depth of approximately 18,000 feet. Eastward of the Wagon Wheel location, the fault becomes parallel to the bedding planes at a depth of some 30,000 feet.

The seismic data and photogeology were evaluated by the U.S. Geological Survey's Water Resources Division and the Pinedale Unit was accepted as worthy of additional tests to identify the hydrological and gas reservoir parameters. Plans for drilling of Wagon Wheel No. 1 were then prepared after acceptance of surface and seismic interpretations and site evaluation.

Wagon Wheel No. 1 is the eleventh well to be drilled on the geologic structure. Eight previous wells proved the existence of gas from about 8,000 to about 14,360 feet. Wagon Wheel No. 1 is the deepest, having reached a total depth of 19,000 feet. Prior to this, Pinedale No. 5 was the deepest at 15,000 feet.

Wagon Wheel No. 1 was drilled to evaluate the Mesaverde equivalent formations below 15,000 feet, and to provide data pertinent to nuclear stimulation regarding



Tw – Wasatch Shales

Qu – Quaternary Mantle Cover & Windblown Sand

Fig. 3 Photogeologic Map of the area surrounding the Wagon Wheel No. 1 location showing its relationship to the lineaments interpreted from aerial photographs.

stratigraphy, hydrology, temperatures, pressures, thickness of reservoir beds, interstitial fluids with the gas reservoirs, porosities and permeabilities, rock mechanics, chemical analysis of formation waters, gas analyses, chemical constituents of the reservoir sediments, and radiochemical analyses.

Figure 4 is a generalized schematic east-west cross section extending from the Wind River Mountains westward through the Pinedale Unit to the Big Piney-LaBarge Platform. The cross section was prepared to provide a simplified illustration of the regional geology and the relationship of the gas-bearing sandstones to the arkosic aquifers.

The Precambrian upthrusted Wind River Range is the source area for the Tertiary arkosic sandstones which represent the upper 8,000 feet of section. These arkoses are water-productive to at least a depth of 7,140 feet. Below 7,972 feet to at least 19,000 feet the sandstones are gas-bearing and could be stimulated by nuclear explosives. The tongue of Wasatch is interpreted from the presence of a salt water zone between fresh and near-fresh waters.

Figure 5 provides more detail of the stratigraphy common to the Pinedale Unit. The pattern of stipled and conglomerate arkose shows the depth of the Tertiary Wasatch and Wasatch equivalent arkosic sandstones which were evaluated by the hydrological study conducted with the U.S. Geological Survey. For the most part, the sediments are poorly cemented, coarse grained arkosic sandstone and varicolored clayey shales. The clays are disaggregated by the drilling fluid resulting in unconsolidated sand grains and minute shale particles when they reach the surface of the ground. From approximately 7,200 feet to 7,972 feet is a transition zone of the overlying arkosic sediments and the underlying gas-bearing sediments. Below the transition zone are sediments which are time equivalents of the Fort Union, Lance, Lewis, Almond, Ericson, Rock Springs, Bacon Ridge (Blair), Lower Mesaverde and Baxter Shale.

From 7,972 feet to the base of the Rock Springs equivalent the sandstones are all light gray, very fine to fine grained, well sorted, hard, nearly impermeable and void of feldspars prevalent in the upper part of the section. Due to the similarity of sediments throughout this interval, it is difficult to pick tops for the individual units in the Mesaverde Group, such as have been identified on the Rock Springs Uplift. The tops shown are more or less arbitrary, based on subtle changes in percentage of sand, amount of coal, and changes from calcareous to siliceous cement.

The Bacon Ridge and the Lower Mesaverde equivalents consist of sandstones and shales with some coal as seen in the overlying sediments. The section referred to as the Bacon Ridge contains massive sandstones within a 1,000 foot

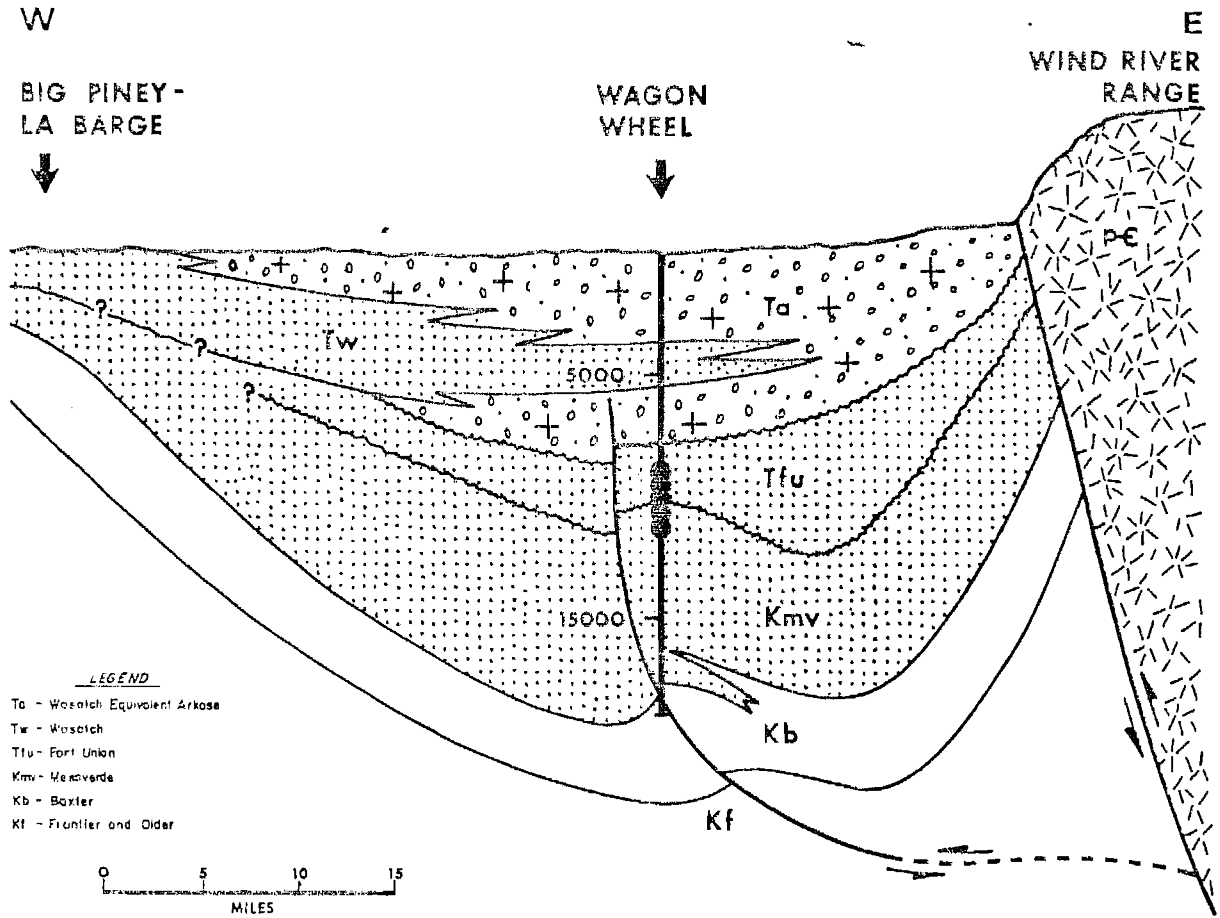


Fig. 4 Generalized Schematic Cross Section of the tectonic features and stratigraphy beneath the Wagon Wheel location and the approximate depths of the proposed five 100KT explosives.

interval. These sandstones were compared microscopically with the Bacon Ridge type section in the Gros Ventre River area of Teton County, 70 miles to the northwest and they appeared similar.

Ordinarily, these massive shoreline Bacon Ridge sandstones are underlain by marine Baxter Shale, but in Wagon Wheel No. 1 there is a section of sandstones, shales and coals quite similar to those of the Rock Springs equivalent, except they are much more calcareous. Palynological studies were attempted on the complete Cretaceous section in an effort to define its age and environment. However, the cores from 13,100 feet to total depth were barren of usable fossils. We interpret the section to be a near-shore continental wedge of Mesaverde equivalent to the Upper Baxter Shale.

Regardless of how individual Mesaverde units are interpreted in the well, 2,950 gross feet of gas-bearing sandstone was drilled before entering the Baxter Shale, resulting in a flow of gas under high pressure at 17,940 feet which almost unloaded the hole of 15 pounds per gallon mud. Wireline logs show essentially the same porosities and permeabilities throughout the gas-bearing section and gas detector response proves the presence of gas in the section. Plans called for production testing this section through casing rather than by drill-stem testing. Consequently, no drill-stem tests were run below 13,202 feet. The liner that was run for the purpose of production testing filled with cement, preventing further evaluation from 13,202 feet to total depth or deeper.

Figure 6 is a comparison of the gas entrained in the mud and the mud weight necessary to maintain the system. The high pressure-low permeability gas reservoirs are typical of the Pinedale Unit. As can be seen, at 15,400 feet the amount of gas and bottom hole pressures required an increase in the mud weight, which continued to a depth of 17,940 feet where the mud weight was once again increased to prevent the gas pressure from unloading the mud system. In order to read the gas contained in an underbalanced mud system in the Pinedale well, it is necessary to increase the electronic parameters of a normal gas detecting unit to its maximum scalar capacity and to lower the gas readings by adding seven parts of air to one part of mud. The Pinedale Anticline is the only structure in the Rocky Mountains with this high pressure reservoir quality over such a thick section.

The gas-bearing sandstones from 7,972 feet to the plugged back total depth of 11,700 feet were reevaluated while drilling the Wagon Wheel No. 1 by cutting eight cores totaling 426 feet, and running three drill-stem tests spaced at intervals of approximately 1,000 feet. The preselected

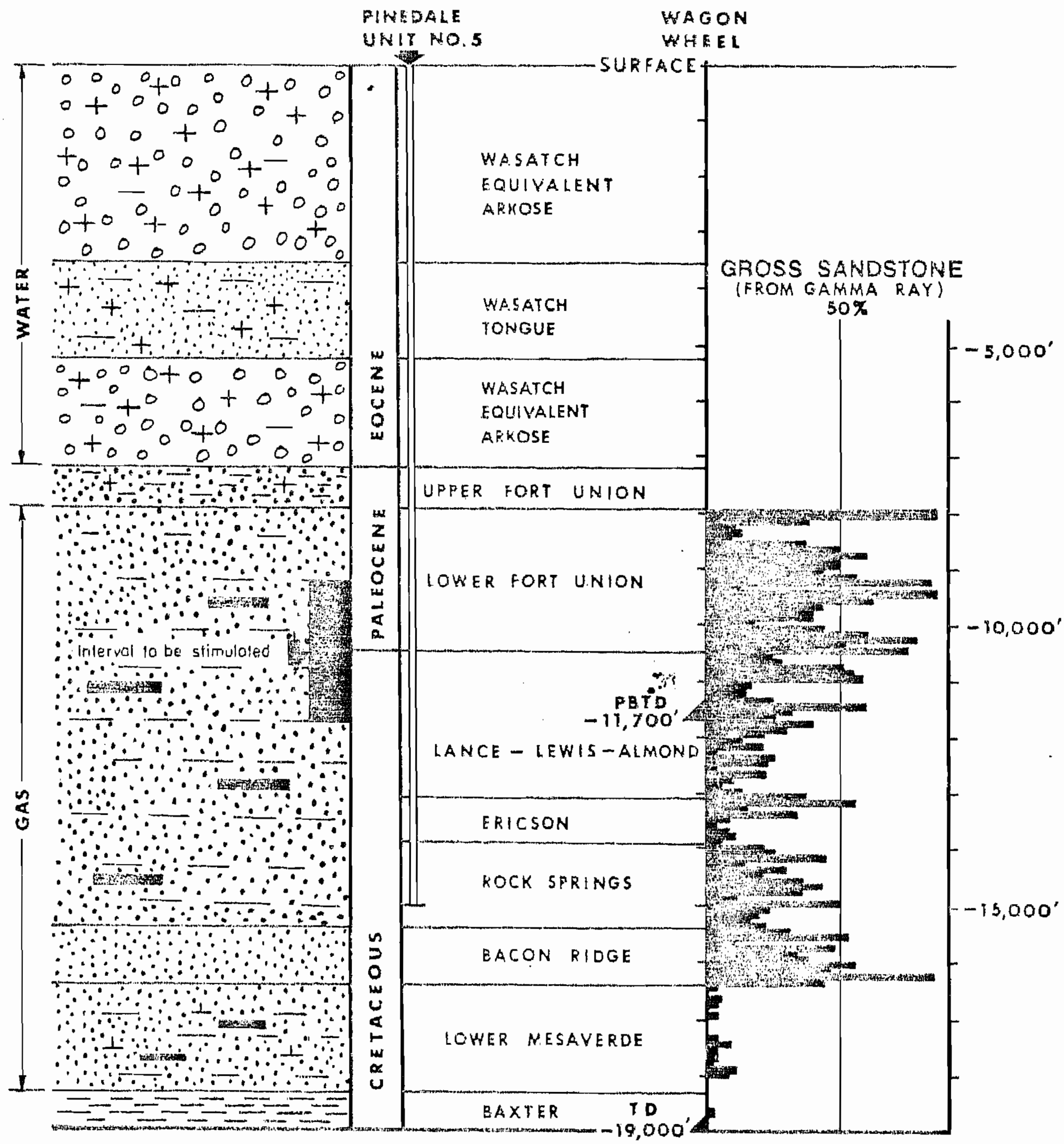


Fig. 5 Stratigraphic column as interpreted beneath the Wagon Wheel location illustrating the intervals of the water bearing sandstones and the gas bearing sandstones.

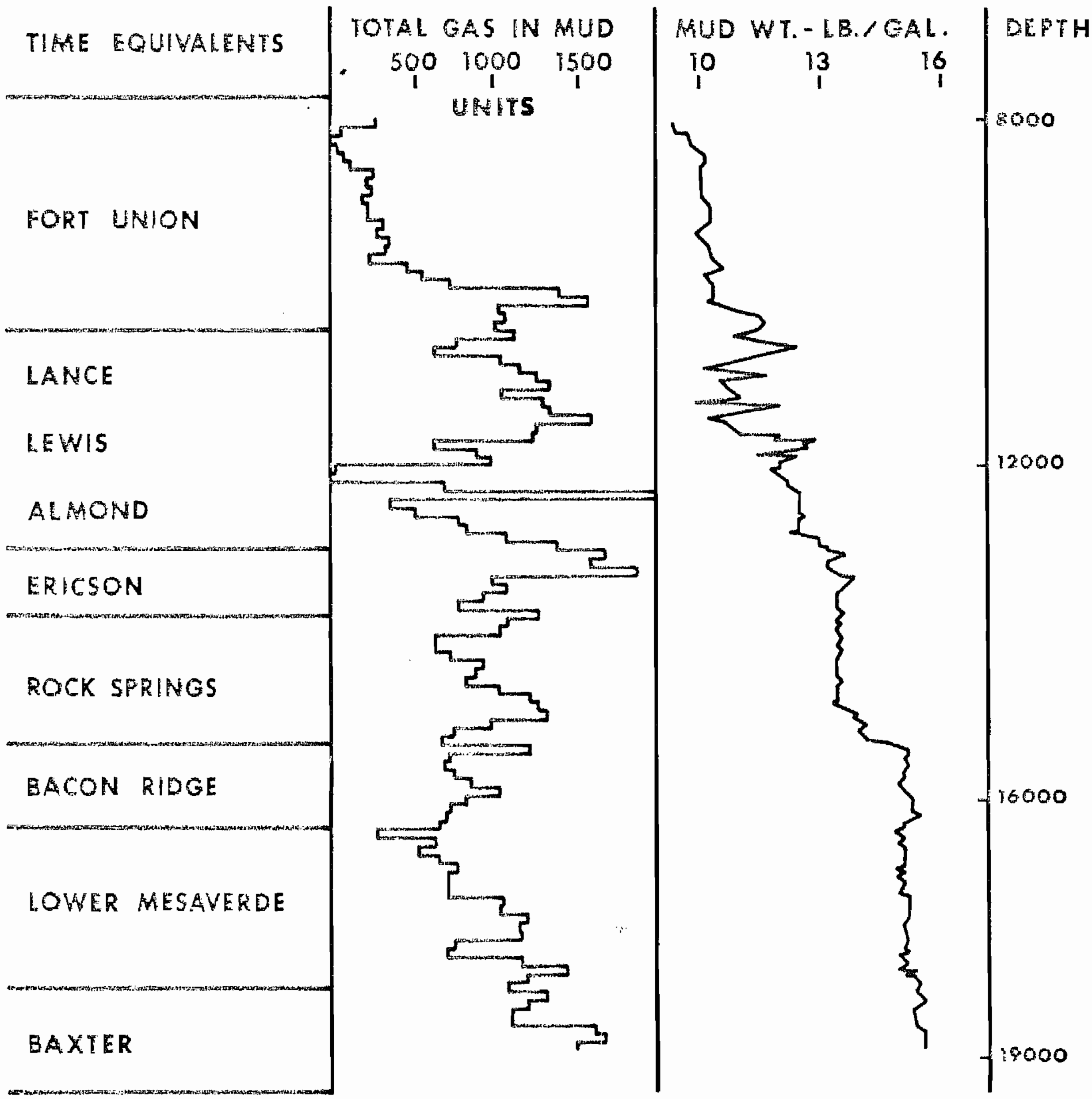


Fig. 6 Comparison of the total gas readings as recorded by the hydrocarbon recording equipment and the weight of the mud required to maintain the system as additional sandstone reservoirs were penetrated.

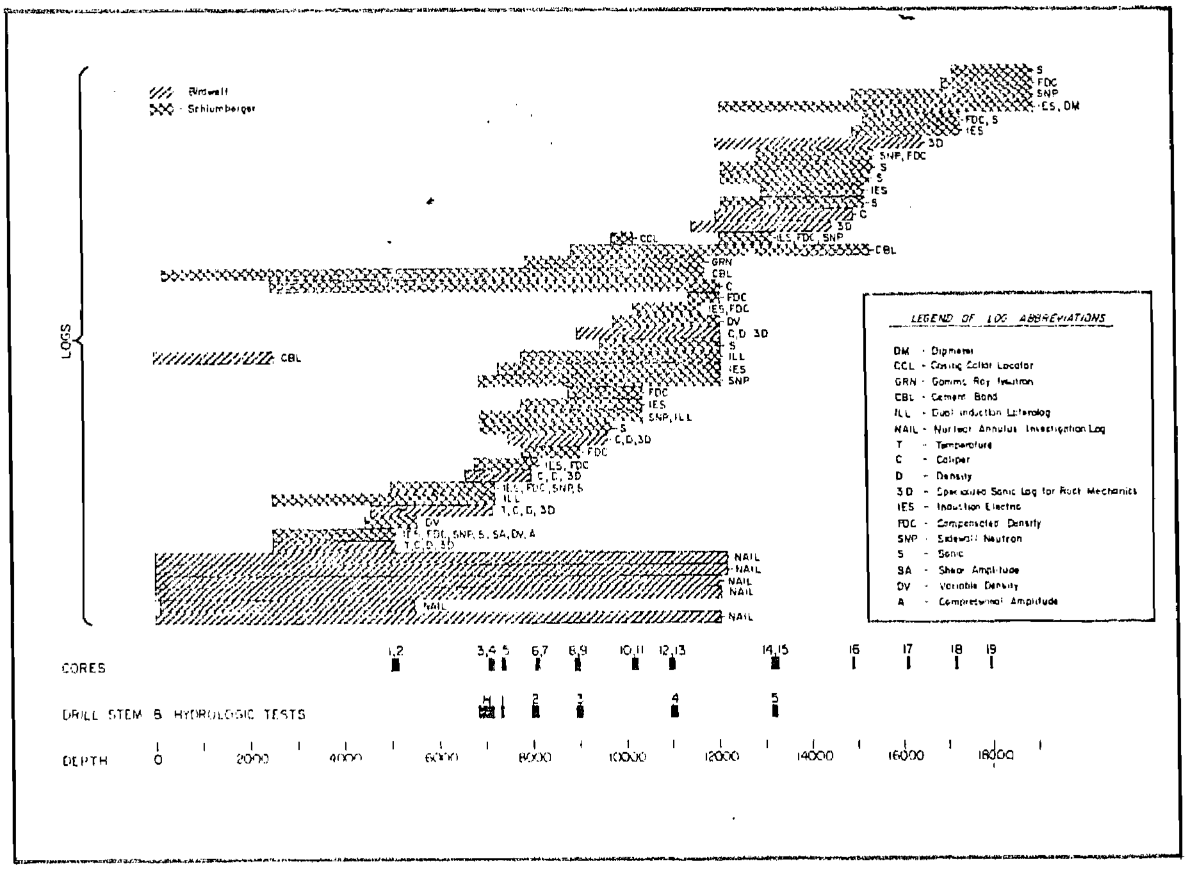


Fig. 7 Graphic summary of all wire line logs, cores and drill stem tests.

intervals were a function of depth to obtain average data over the entire column. The purpose of preselecting intervals was to reconfirm the existence of gas-bearing sediments, prove the presence or absence of producible formation water, measure temperature, determine average pressure, average porosity, permeability, water saturation, and finally, to provide an average sample of the sandstones and shales for chemical and mechanical analysis. In addition, electric logs were run as often as possible to reduce the effects of invasion by filtrate water and to obtain an accurate reading of the spontaneous potential for a reliable interpretation of the formation water resistivity (see Graphic Summary, fig. 7).

Interpretation of the acquired data determined that the Pinedale Unit had the necessary requisites to be classified as a candidate for nuclear stimulation. The important questions had been answered reconfirming the presence of natural gas in each of the sandstones drilled below 7,972 feet and that the gas-bearing sandstones would not produce formation water under normal conditions. The tests also reconfirmed what was already apparent from production tests in eight previous wells in the unit: a conventionally completed well will not yield a commercial flow of gas.

To supply the data required for the project it was necessary for El Paso to drill two hydrological test wells in addition to the deep test which may be used as an emplacement hole. The two hydrological test holes were drilled offsetting Wagon Wheel No. 1. Wagon Wheel Water Well No. 1, 90 feet west of Wagon Wheel No. 1, was drilled to a depth of 2,501 feet to evaluate the groundwater conditions and to serve as a supply well for the drilling of Wagon Wheel No. 1.

The Wagon Wheel No. 1 was commenced in October, 1969 and was completed in November, 1970. Figure 8 shows the casing program to 12,086 feet as well as the planned program for explosives emplacement. A 25-inch conductor pipe was set at 25 feet. Sixteen inch surface casing was cemented at a depth of 2,478 feet. All testing, coring and logging were accomplished in an 8¾ inch pilot hole to a depth of 12,100 feet. This hole was then reamed to 14¾ inches from 2,478 to 12,100 feet where 10¾ inch casing was set at 12,086 feet. A 9½ inch hole was drilled to total depth. During cementing of the 7-5/8 inch liner, from 11,755 to 19,000 feet, the liner filled with cement resulting in the decision to abandon the lower portion of the hole to maintain the upper part of the hole in readiness for possible use as a nuclear emplacement hole.

The second hydrological well, 630 feet west-southwest of Wagon Wheel No. 1, was drilled to test two additional zones to a depth of 5,200 feet. Drilling operations commenced in April of 1971 and were completed during May of 1971. A production string of 7-inch casing was cemented at 5,200 feet. After the completion of production tests of the aquifers, a production packer on tubing was set above the lower perforations for future measurements of static water levels for the two zones.

Figure 8, a diagram of the planned emplacement hole, shows the three different zones of water in the Wagon Wheel No. 1 site area, as determined by the hydrological test program. The lower portion of the drawing shows the approximate position of the explosive assembly on 7-inch casing in relation to the transition zone of possible water-productive sediments, subpotable water, saline water and the uppermost fresh waters. A cement plug will cover the explosive cannister up to a depth of 7,200 feet.

Groundwater occurs from essentially the ground surface to a depth of approximately 7,200 feet. This column of water-yielding sediments was programmed as one of the major points for evaluation of Project Wagon Wheel and was tested in five intervals.

Nineteen sets of perforations were tested in Wagon Wheel Water Well No. 1 between 130 and 2,432 feet (fig. 9). The interval 2,312 to 2,427 feet was tested in Wagon Wheel Water Well No. 2. Both of these tests confirmed the presence of fresh potable water which can be pumped at high enough rates for domestic use (about 52 GPM). The third test between 4,937 to 5,108 feet pumped a low flow rate (3.2 GPM) of salt water. The deepest recovery of water was from the interval between 6,868 and 7,140 feet. A swab test produced subpotable water, again at a very low rate of flow (3.5 GPM). A drill-stem test to define the approximate limit of the water-yielding sandstones was run between the depths of 7,275 and 7,400 feet. This test resulted in a recovery of gas and no water. Therefore, potable water exists to a depth of 3,730 feet, salt water down to a depth of 5,630 feet and subpotable water to a depth of 7,140 feet.

Figure 9 shows the induction resistivity from the surface down to the top of the gas-bearing strata. The sharp reduction in resistivity at 3,730 feet is interpreted as the top of the salt water-bearing sediments. A sharp decrease in the spontaneous-potential deflection at 5,630 feet, coupled with the increase of resistivity, is interpreted as the top of the subpotable water. The zone of salt water is interpreted, then, as the tongue of Wasatch shown in figure 4. The zone between 7,140 and 7,972 feet is believed to be a transition between the overlying arkosic water-bearing sediments and the underlying gas-bearing sediments. Although the drill-stem test did not yield water, it is assumed, for the purpose of safety, that water might be produced if the zone were artificially stimulated. With this assumption in mind, the upper explosive has been planned for a depth of 9,220 feet to prevent fracturing of the transition zone, which in turn will provide an additional buffer between the stimulated interval and any aquifer.

Project Wagon Wheel will be the first test to stimulate natural gas reservoirs with multiple explosives fired in sequence. Figure 10 shows the relative position of each of the five 100 kiloton explosives to be placed at 9,220 feet, 9,680 feet, 10,230 feet, 10,860 feet and 11,570 feet. The elapsed time between shots will be five minutes to allow sufficient time for the seismic effect to subside. The results of each device have been predicted by using laboratory and field measurements obtained from rock mechanic studies of the Wagon Wheel data, and comparing to data from previous experiments such

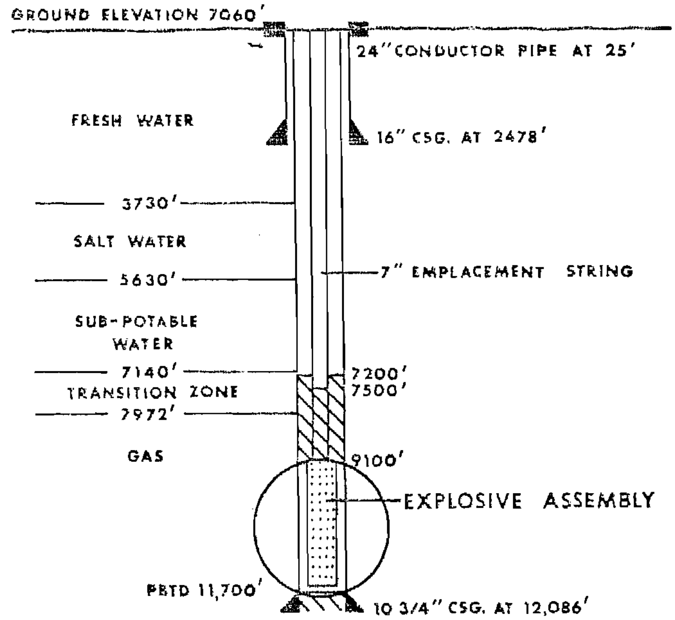


Fig. 8 Schematic drawing of the cased Wagon Wheel No. 1 Emplacement Hole showing the hydrological interpretation and its position above the explosive assembly attached to the 7" drill pipe emplacement string.

as Gasbuggy and various tests at the AEC Nevada Test Site. The analysis of these data as interpreted by computer calculations resulted in the calculated effects as shown on Figure 10. A cavity radius of 88 feet for each of the five explosives is expected to produce a continuous rubble chimney of 80 to 100 feet in radius from 9,000 to 11,650 feet. A zone of shattered rock will exist from a radius of 120 to 140 feet with shear fractures or increased permeabilities out to a radius of 220 feet. The tensile fracturing, which is the widest extent of artificially produced fractures, will extend out to a radius of 440 feet.

A relationship was established between porosity and water saturation such that only sandstones having greater than 7.5% porosity and less than 60% water saturation would contribute to calculations of gas in place. The gas in place in the remaining sandstones with less porosity or higher water saturation was considered of insignificant amount. Therefore, the following parameters were used in the calculations:

A) Average temperature - A surface temperature of 72° F and a gradient of 1.252° per 100 feet.
B) Average pressure - 6,533 psi at 10,000 feet with a pressure gradient of 65.1 psi per 100 feet.
C) Average permeability (by conventional core analysis) - 0.068 Md. (In situ permeability used for predicted gas production - 0.0034 Md.)
D) Net pay between 8,000 to 11,800 feet - 687 feet.
E) Gas in place - 252 Bcf per square mile between the interval 8,000 to 11,800 feet.
F) Specific gravity - 0.613.
G) Stimulated interval - 9,000 to 11,650 feet (net sandstone - 568 feet; gross sandstone - 1,135 feet).

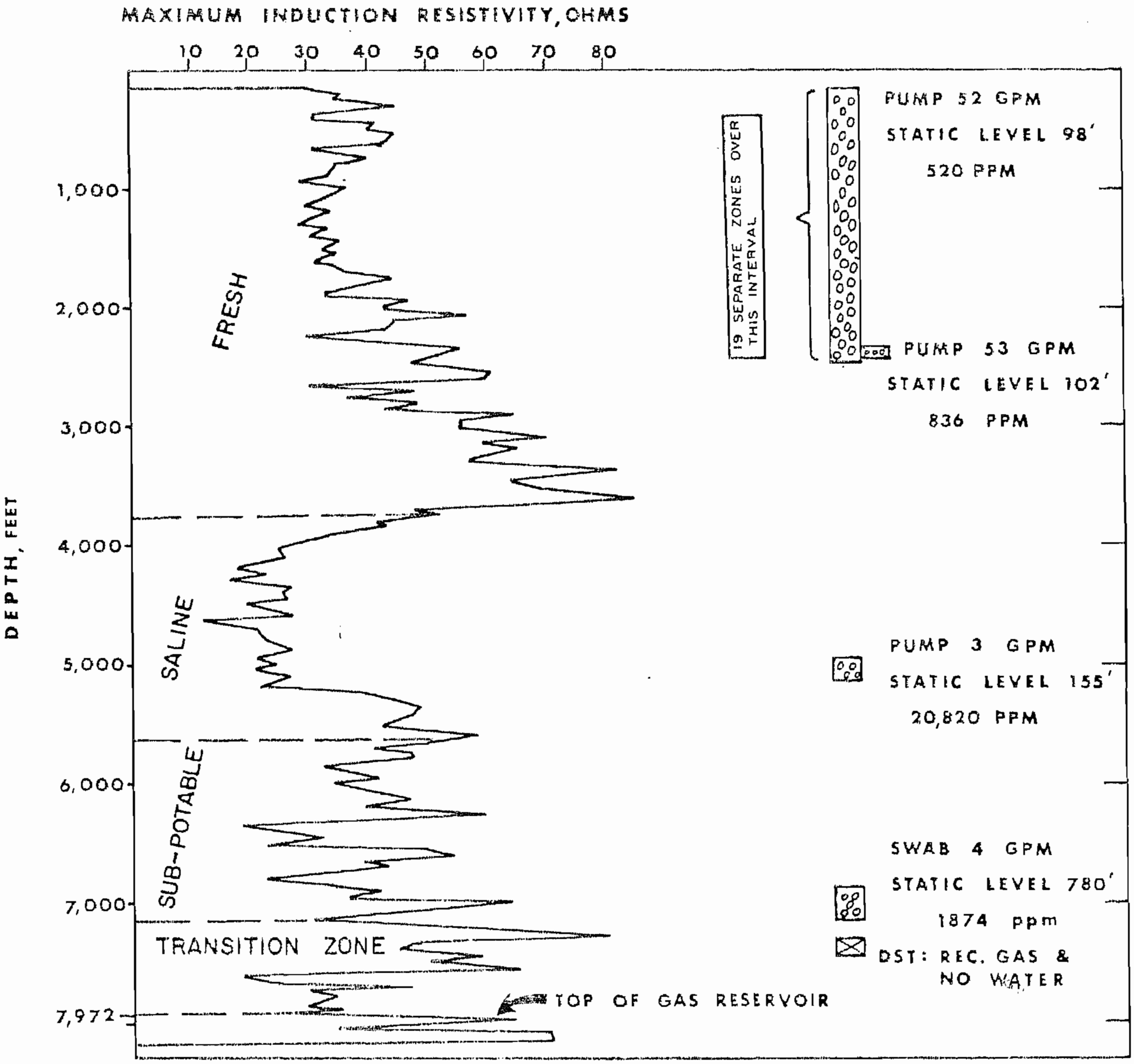


Fig. 9 The quality of the aquifers as defined by the Wagon Wheel hydrological investigation in relation to production characteristics and induction resistivity in Wagon Wheel No. 1, Wagon Wheel water well No. 1 and Wagon Wheel water well No. 2.

Total gas in place calculations assume that the individual sandstone layers will extend continuously for one square mile and is not derived from the gross sandstone thickness as shown in figure 5. As a comparison to the net pay used in the reserve calculations, the gross sandstone over the same interval was approximately 1,600 feet. Gas in place over the stimulated interval is estimated to be 207 Bcf per square mile.

El Paso, Lawrence Livermore Laboratory and the Bureau of Mines, using the above data, predicted essentially the same production with independent computer programs. The estimated productive capacity of the stimulated interval from 9,000 to 11,650 feet, over a twenty-year period, is shown on figure 11. An initial flow rate is assumed at 35 MMcfd until the chimney pressure decreases to 625 psi and continues to decrease to a flow rate of 1.8 MMcfgd at the end of a twenty-year period. The twenty-year cumulative production of 21.2 Bcf is approximately 10.2% of the gas in place. It is also predicted that 19.3 Bcf will be from the stimulated formation and 1.9 Bcf will originate from the chimney at the start of production.

CONCLUSIONS

The numerous studies performed to obtain information for evaluation of nuclear stimulation in the Pinedale Unit and

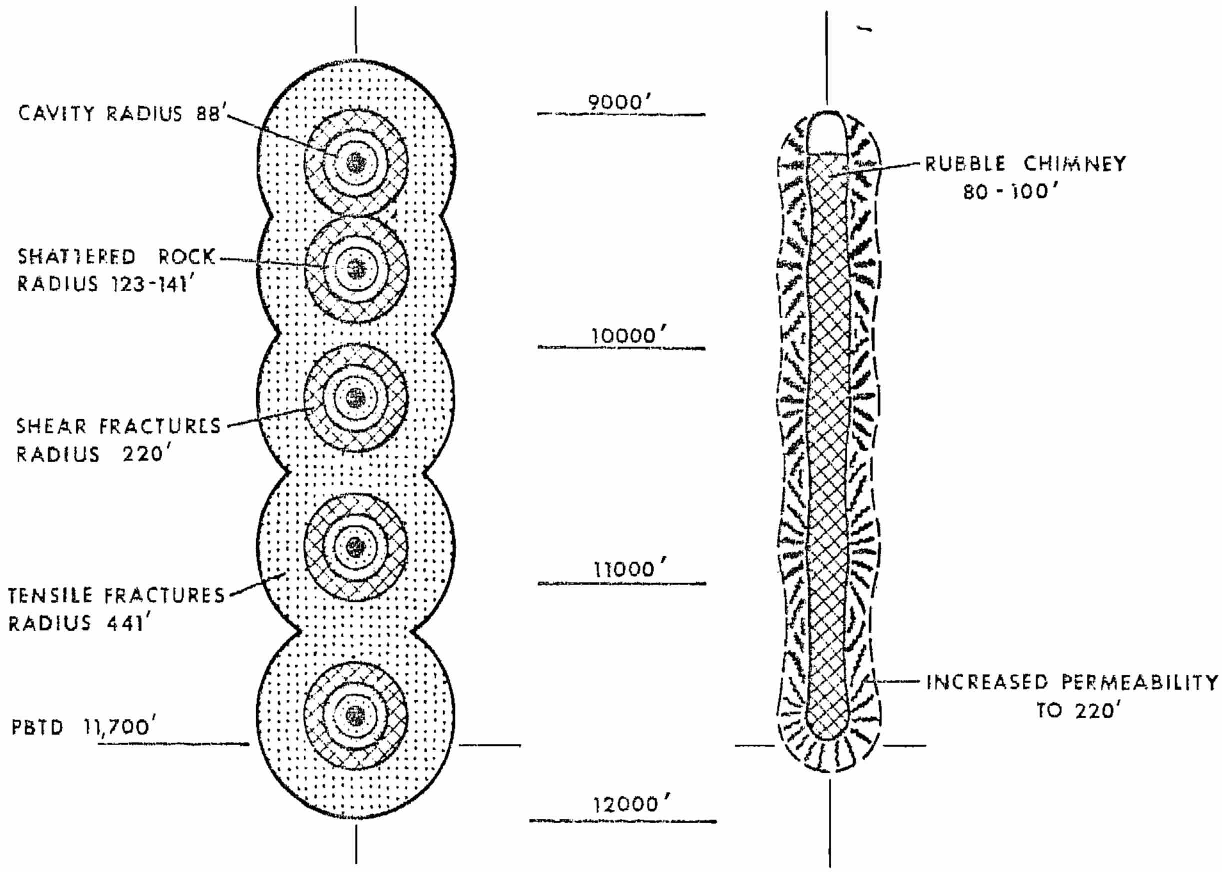


Fig. 10 Detailed cross section showing the depths of the five 100KT explosives, the calculated resultant chimney and associated fracture system.

design of Project Wagon Wheel have involved substantial expenditures to develop geological information beyond that developed in conventional exploration wells. This additional information included, 1) definition of hydrologic conditions from the ground surface to a depth well below the interval of planned stimulation; 2) mechanical properties for rock mechanic studies; 3) chemical composition of both reservoir rock and shale strata in the reservoir section; and 4) the effect of both confining pressure and water saturation to develop in situ permeability. Drill-stem and production testing to determine the reservoir properties of each of the many sandstone strata expected to contribute to production was virtually impossible. Permeability determination for a single sandstone strata is being obtained by production tests in an attempt to accurately predict future flow rates from a stimulated well.

It is anticipated that additional experience in evaluating prospects for nuclear stimulation will result in methods whereby costs for obtaining reservoir information can be reduced substantially.

The Wagon Wheel Program has shown that data normally developed in an exploration program are useful in deciding whether to invest in additional drilling or testing for evaluation of nuclear stimulation. Such data, including aerial photography, seismic profiles, downhole pressures and temperatures, porosities, conventional permeability measurements, water saturation and stratigraphy provides a basis for comparison with previous nuclearly stimulated wells. However, design of the next few nuclear stimulation projects in new areas probably will require developing the data with more precision than results from normal practices. Additional information will augment the existing data to permit calculation of nuclear effects, safety evaluation, hydrological conditions and the relationship of fractures and faults to the overall project.

Geologically, the Pinedale Unit is an excellent prospect for a test of nuclear stimulation. Natural gas is present in sandstone strata at depths ranging from 8,000 to 19,000 feet. None of the drill-stem or production tests, in this interval, have produced water. In addition, correlations of the tested intervals with cores and wireline logs over the untested interval indicates that no mobile water exists between 7,972 and 11,700 feet. Nuclear stimulation is the only practical means of developing a continuous vertical section of several thousand feet in thickness to achieve production of billions of cubic feet of natural gas at feasible costs.

The test programs and project design will be directed with utmost concern for the protection of the aquifers overlying the top of the gas reservoirs. El Paso is currently sponsoring environmental studies and will continue to

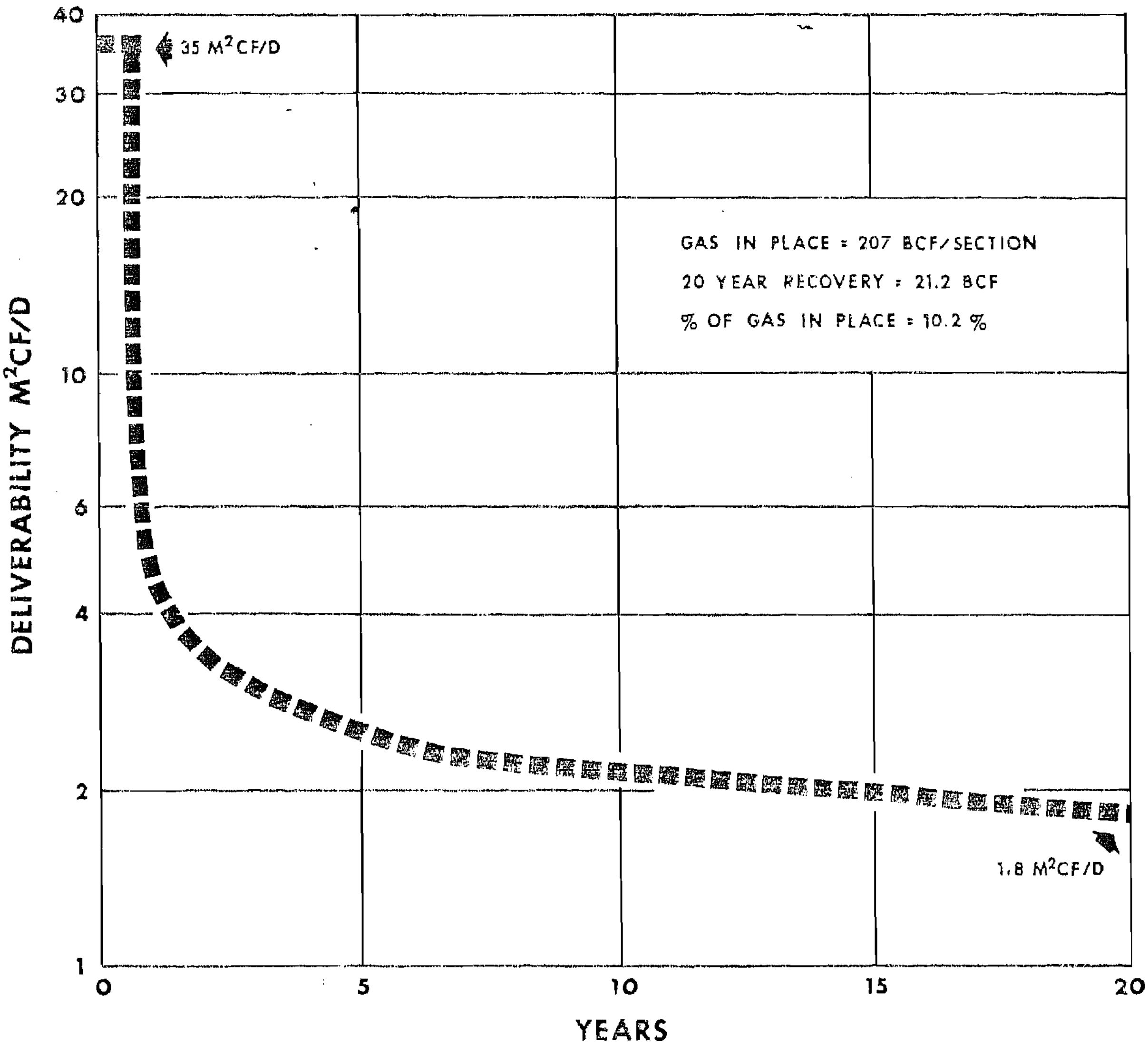


Fig. 11 Graph of predicted gas production over a twenty year period.

sponsor programs for the economical and safe recovery of natural gas. This information, as well as production test results, is essential to determine the extent to which nuclear stimulation will provide a practical means for recovering gas from the Pinedale Unit and other tight reservoirs in the Rocky Mountain area.

SELECTED BIBLIOGRAPHY

El Paso Natural Gas Company, 1971, Project Wagon Wheel definition plan, U.S. Atomic Energy Comm. Open File Draft Report.

———, 1971, Project Wagon Wheel technical studies report, U.S. Atomic Energy Comm. Open File Report.

Martin, W.B. and Shaughnessy, J., 1969, Project Wagon Wheel, in Wyoming Geol. Assoc. Guidebook, 21st Annual Field Conference, p. 145-152.

Shaughnessy, J., 1969, Completion report, Wagon Wheel Water Well No. 1, El Paso Natural Gas Company - U.S. Atomic Energy Comm. Open File Report.

———, 1971, Completion report, Wagon Wheel Water Well No. 2, El Paso Natural Gas Company - U.S. Atomic Energy Comm. Open File Report.

———, and Butcher, R.H., 1970, Project Wagon Wheel interim report of Wagon Wheel No. 1 at casing point depth of 12,106 feet, El Paso Natural Gas Company U.S. Atomic Energy Comm. Open File Report.

Shaughnessy, J., et al, 1970, Project Wagon Wheel hydrological test program, U.S. Atomic Energy Comm. and El Paso Natural Gas Company Open File Report.

U.S. Atomic Energy Comm., 1972, (two drafts), Environmental statement, Wagon Wheel gas stimulation project, Sublette County, Wyoming, WASH-1524.