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Gary B. Glass, State Geologist

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# WYOMING'S CARBON DIOXIDE RESOURCES

by

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## ABSTRACT

In Wyoming, carbon dioxide ($CO_2$) is concentrated in reservoirs of Paleozoic age at La Barge, Bruff, Church Buttes, and Butcher Knife Springs fields on the Moxa arch in the Greater Green River Basin. Table Rock and Brady fields in the eastern Greater Green River Basin, Whitney Canyon-Carter Creek Field in the Overthrust Belt, and Madden Field in the Wind River Basin also have reservoirs that contain significant volumes of carbon dioxide. Other areas of the State have wells in reservoirs that can produce gas rich in carbon dioxide. These other reservoirs, however, are small and only contain small volumes of natural gas, or the carbon dioxide concentrations are not high enough to contribute significant resources of carbon dioxide.

Wyoming's estimated original resources of carbon dioxide were 153.89 trillion cubic feet. After cumulative production of 0.63 trillion cubic feet is subtracted, Wyoming has remaining carbon dioxide resources of 153.26 trillion cubic feet (through December 31, 1990). The remaining carbon dioxide resources consist of 122.06 trillion cubic feet of identified resources and 31.20 trillion cubic feet of undiscovered resources. Of the 122.06 trillion cubic feet of remaining identified resources of carbon dioxide estimated for Wyoming, 111.26 trillion cubic feet occur in the Madison Limestone at La Barge anticline. In addition, another 6.12 trillion cubic feet occur at La Barge anticline in other reservoirs of Paleozoic age. The remaining 4.68 trillion cubic feet of identified carbon dioxide resources are found in Paleozoic formations at Bruff, Church Buttes, Butcher Knife Springs, Whitney Canyon-Carter Creek, Table Rock, and Madden fields. The La Barge anticline contains 117.38 trillion cubic feet or 96.2 percent of all remaining identified carbon dioxide resources in the State.

Undiscovered resources of carbon dioxide are an estimated 31.20 trillion cubic feet. Paleozoic formations below a depth of 15,000 feet in the Greater Green River Basin are expected to contain most of these undiscovered resources. Undiscovered resources are subdivided into 15.60 trillion cubic feet of recoverable undiscovered resources and 15.60 trillion cubic feet of marginal and subeconomic undiscovered resources.

Wyoming's remaining recoverable identified resources of carbon dioxide (as of December 31, 1990) are an estimated 60.715 trillion cubic feet. An estimated 58.44 trillion cubic feet of this total occur at La Barge anticline. Another 15.60 trillion cubic feet of recoverable undiscovered resources brings the total recoverable resources of carbon dioxide to 76.315 trillion cubic feet. Production from Wyoming's recoverable resources is currently about 127 billion cubic feet a year and almost all of the production is from the Madison Limestone at La Barge anticline.

## INTRODUCTION

This report provides estimates of Wyoming's original, remaining, and recoverable identified and undiscovered resources of carbon dioxide. The report also includes a tabulation of the reservoir parameters that were used to make the estimates (**Table 1**). Definitions of the resource terms used in this paper are modified from U.S. Geological Survey Circular 860 (Dolton and others, 1981). Although most of the estimated carbon dioxide in Wyoming occurs in the Madison Limestone at La Barge anticline in southwestern Wyoming, estimates are also included for other reservoirs that contain significant volumes of carbon dioxide.

Table 1. Reservoir parameters uses to estimate original identified resources of carbon dioxide for various areas and formations in Wyoming.

| Resource Area or Field and Formation | Area (acres) | Average thickness (feet) | Average porosity (percent) | Average pressure (lbs/in$^2$) | Temperature (°R)[1] | Average gas saturation (percent) | Average gas compressibility factor | Average CO2 composition of gas (percent) |
|---|---|---|---|---|---|---|---|---|
| La Barge (Madison) | 682,600 | 400 | 5 | 7,105 | 740 | 80 | 1.01 | 70 |
| La Barge (Bighorn) | 115,200 | 60 | 8 | 6,805 | 760 | 75 | 0.92 | 85 |
| La Barge (Tensleep) | 38,400 | 50 | 5 | 3,160 | 730 | 75 | 0.81 | 64 |
| La Barge (Phosphoria) | 38,400 | 50 | 5 | 3,165 | 725 | 75 | 0.81 | 65 |
| La Barge (Darby) | 19,200 | 23 | 4 | 2,975 | 750 | 75 | 0.80 | 67 |
| Bruff (Madison) | 7,680 | 200 | 3 | 6,015 | 760 | 80 | 0.87 | 83 |
| Church Buttes (Madison) | 12,160 | 300 | 5 | 8,005 | 795 | 77 | 0.99 | 86 |
| Church Buttes (Morgan) | 12,160 | 64 | 12 | 8,035 | 790 | 75 | 1.20 | 24 |
| Butcher Knife Springs (Morgan) | 5,000 | 24 | 7 | 4,565 | 745 | 75 | 1.00 | 22 |
| Whitney-Canyon-Carter Creek (Madison) | 19,500 | 450 | 6 | 3,335 | 670 | 75 | 0.94 | 6 |
| Table Rock (Madison) | 15,000 | 160 | 13 | 5,315 | 790 | 75 | 1.06 | 16 |
| Table Rock (Weber) | 15,000 | 68 | 5 | 5,395 | 785 | 75 | 1.08 | 10 |
| Brady (Weber) | 5,800 | 180 | 9 | 6,005 | 700 | 79 | 1.07 | 27 |
| Brady (Nugget) | 5,800 | 100 | 11 | 4,915 | 680 | 75 | 0.83 | 72 |
| Madden (Madison) | 69,120 | 145 | 7 | 6,700 | 875 | 75 | 1.11 | 17 |

[1]°R = degrees Rankine (460 + degrees Fahrenheit).

## OCCURRENCES OF CARBON DIOXIDE IN WYOMING

Several reservoirs in large existing fields have relatively high concentrations and significant resources of carbon dioxide in their natural gases (**Figure 1**). In 1961, Mobil Oil Company discovered very large carbon dioxide resources in the Madison Limestone as well as in several other Paleozoic formations at La Barge anticline in southwestern Wyoming. However, development of these resources (by Exxon) did not begin until the early 1980s. In 1985, Monsanto Oil Company discovered large carbon dioxide resources in the Madison Limestone at Madden anticline in the Wind River Basin (Brown and Shannon, 1989a, b).

In addition, the U.S. Bureau of Mines has analyzed natural gas for carbon dioxide and other components for many years (Moore and Sigler, 1987a; 1987b; 1988; and Hamak and Sigler, 1989). The U.S. Bureau of Mines' analyses enabled the author to identify several areas in Wyoming where reservoirs contain natural gases composed of more than five percent carbon dioxide. These reservoirs are in formations that are Ordovician to Tertiary in age (**Figure 2**). Many of these reservoirs, however, are not included in this resource assessment because one or both of the following conditions severely limit their carbon dioxide resources:

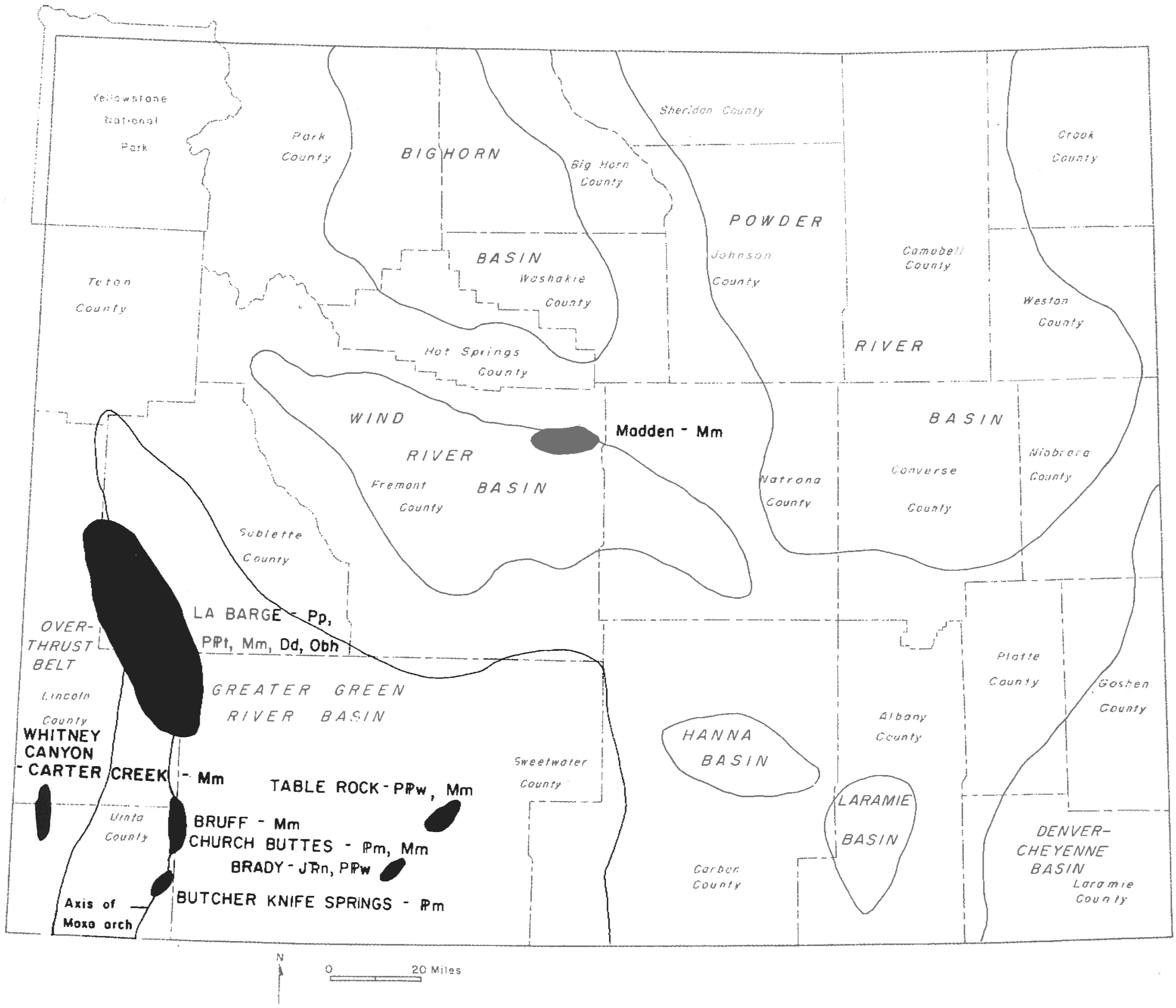
1) The reservoir is small and only contains small volumes of natural gas.
2) The carbon dioxide content of the natural gas in the reservoir is relatively low.

Recent development of carbon dioxide resources at La Barge anticline, recent drilling at Madden anticline, and the U.S. Bureau of Mines' analyses formed the basis for this estimate of original and remaining identified carbon dioxide resources in Wyoming. Significant reservoirs were assessed by using all available reservoir parameters (**Table 1**). **Figure 3** shows the stratigraphic position and geologic ages of rocks in the different areas of Wyoming that contain significant carbon dioxide resources.

## ORIGIN OF CARBON DIOXIDE IN NATURAL GAS

Carbon dioxide is a common component of natural gas; however, the high concentrations and large quantities that occur in several reservoirs in Wyoming are uncommon. These higher concentrations and larger quantities of carbon dioxide probably resulted from more than one of the following processes:

1) Carbon dioxide gas could have migrated from the Quaternary intrusives on the northern end of the Rock Springs uplift into Paleozoic reservoirs in the Greater Green River Basin (Stilwell, 1989). Carbon dioxide is generally the principal carbon gas from fumaroles in volcanic areas (Krauskopf, 1967).
2) Thermal degradation of liquid hydrocarbons forms carbon dioxide (as well as methane, water, nitrogen, and hydrogen sulfide) (Orr, 1974).
3) Anhydrite can provide sulfate anions that react with methane to form carbon dioxide and hydrogen sulfide (Hill, 1990). Anhydrite is present in most Paleozoic formations in Wyoming.
4) Sulfuric acid forms when hydrogen sulfide is oxidized. The sulfuric acid reacts with carbonates to produce carbon dioxide (Hill, 1990). Paleozoic formations in Wyoming contain large volumes of carbonate rock and most reservoirs with high carbon dioxide concentrations in the natural gas contain hydrogen sulfide as well.




## KEY TO FORMATION NAMES

JURASSIC - TRIASSIC
JTRn Nugget Sandstone

PERMIAN
Pp Phosphoria Formation

PERMIAN - PENNSYLVANIAN
PIPw Weber Sandstone
PIPt Tensleep Sandstone

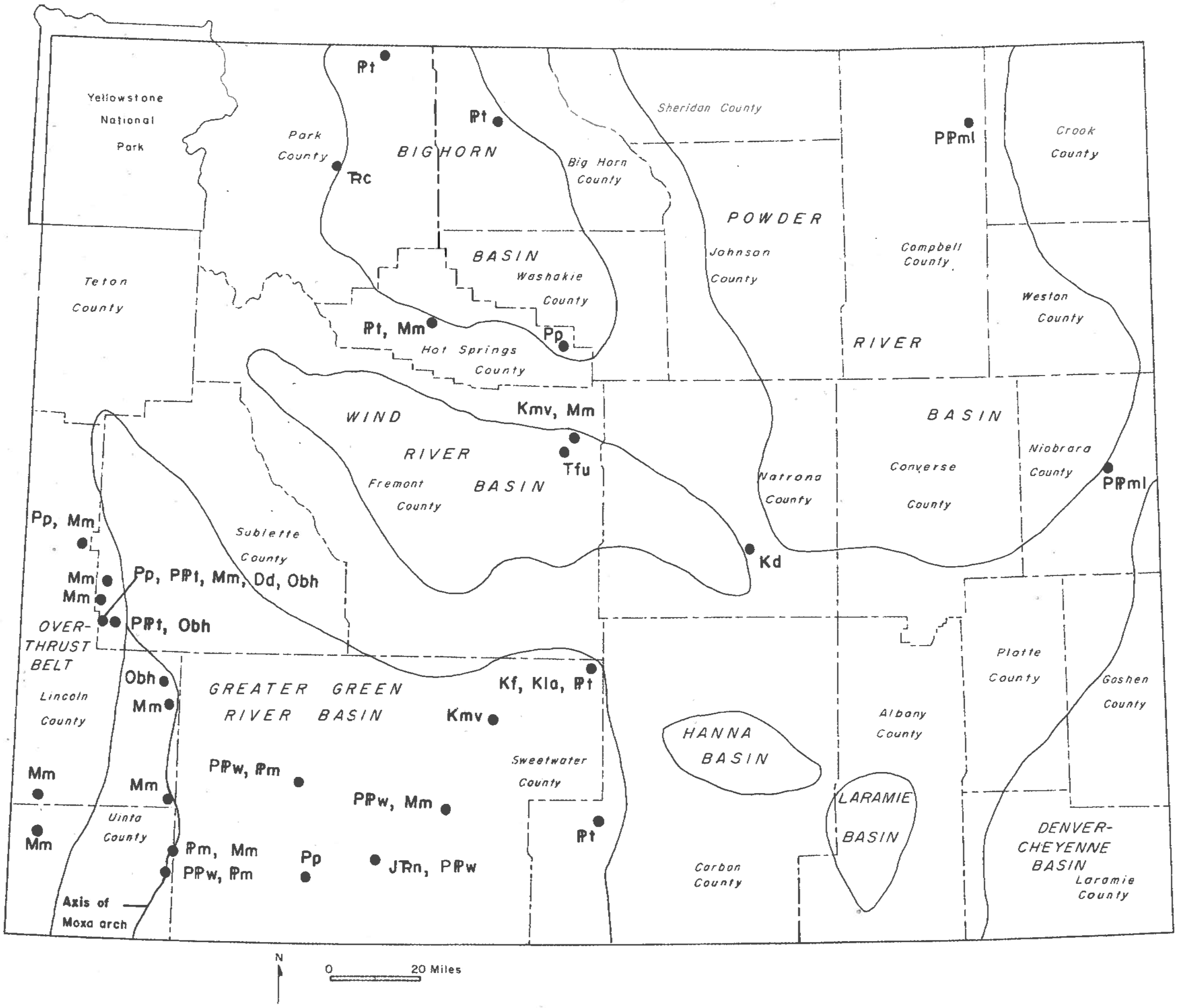
PENNSYLVANIAN
IPm Morgan Formation

MISSISSIPPIAN
Mm Madison Formation

DEVONIAN
Dd Darby Formation

ORDOVICIAN
Obh Bighorn Dolomite

Figure 1. Wyoming fields with formations containing significant carbon dioxide resources.




## KEY TO FORMATION NAMES

**TERTIARY**
- Tfu — Fort Union Formation

**CRETACEOUS**
- Kmv — Mesaverde Formation
- Kf — Frontier Formation
- Kd — Dakota Sandstone
- Kla — Lakota Formation

**JURASSIC - TRIASSIC**
- JTRn — Nugget Sandstone

**TRIASSIC**
- TRc — Chugwater Formation or Group

**PERMIAN**
- Pp — Phosphoria Formation

**PERMIAN - PENNSYLVANIAN**
- PIPml — Minnelusa Formation
- PIPw — Weber Sandstone
- PIPt — Tensleep Sandstone of the western Greater Green River Basin

**PENNSYLVANIAN**
- IPt — Tensleep Sandstone of the Bighorn Basin and easternmost Greater Green River Basin
- IPm — Morgan Formation

**MISSISSIPPIAN**
- Mm — Madison Limestone

**DEVONIAN**
- Dd — Darby Formation

**ORDOVICIAN**
- Obh — Bighorn Dolomite

Figure 2. Areas in Wyoming where the U.S. Bureau of Mines has identified reservoirs with natural gases that are more than five percent carbon dioxide.

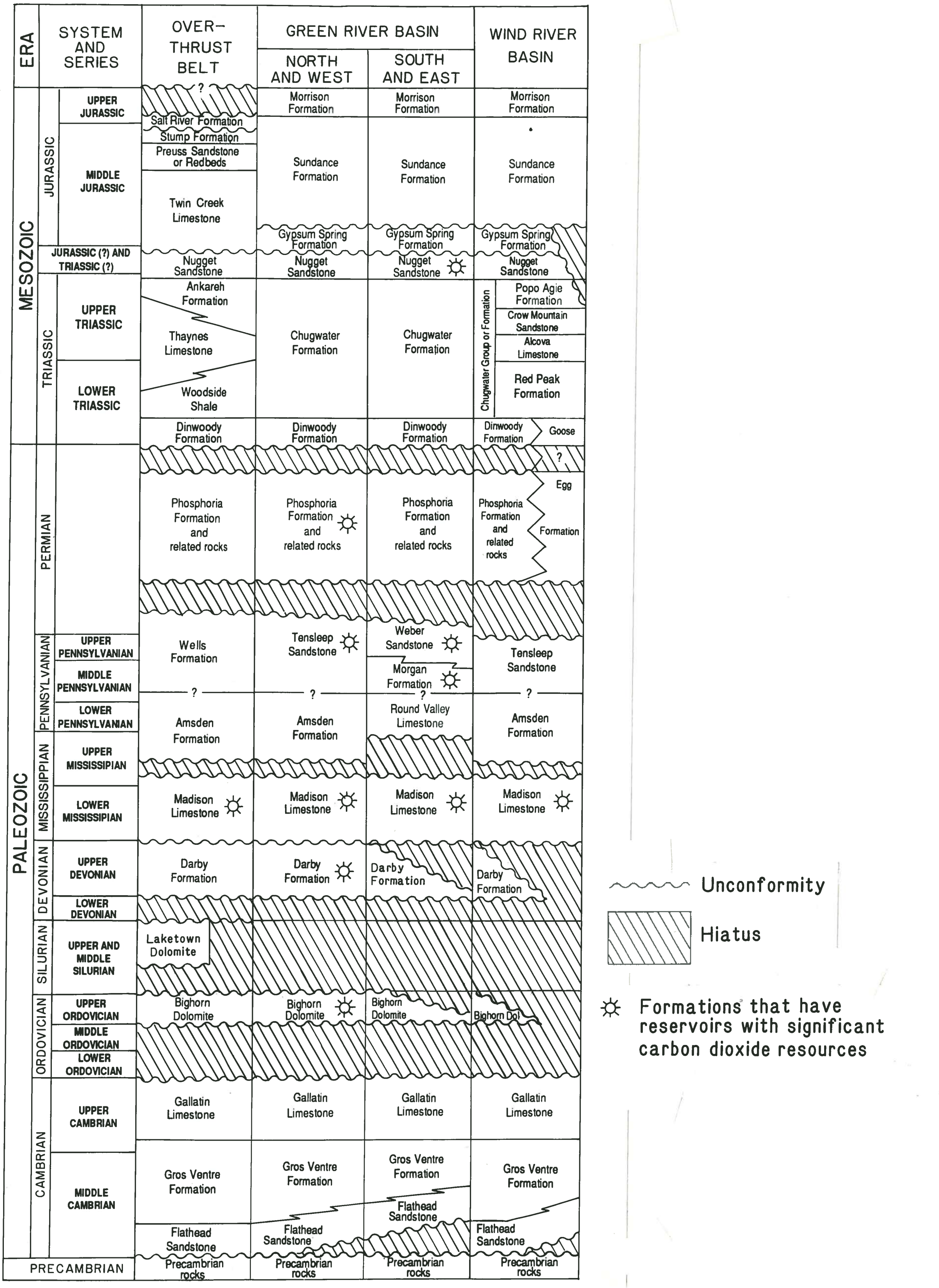



Figure 3. Stratigraphic correlation chart of Precambrian through Jurassic rocks in areas of Wyoming where significant carbon dioxide resources are found (modified from Love and others, 1987).

## USES FOR CARBON DIOXIDE

Carbon dioxide has a wide variety of uses. Water saturated with carbon dioxide at three to four atmospheres of pressure becomes carbonated water, which is essential for the huge soda-water beverage industry. Because carbon dioxide is approximately 1.5 times denser than air and does not support combustion, liquid or gaseous carbon dioxide under pressure is used in fire extinguishers. The textile, leather, and chemical industries use carbon dioxide as a weak acid. Carbon dioxide is also used to prepare food, to purge tanks and pipelines, to manufacture aspirin, to weld, to propel aerosols, to stimulate respiration, to manufacture carbonates, and to produce an inert atmosphere. Solid carbon dioxide is called dry ice because it vaporizes without melting. Dry ice is a clean and convenient refrigerant when sub-zero temperatures are required.

Another very significant use for produced carbon dioxide in Wyoming is in enhanced oil recovery (EOR) projects. Some EOR projects inject carbon dioxide to recover additional oil left behind in reservoirs. Normally between 60 and 70 percent of the original oil is left in a reservoir after primary and secondary operations are completed. When carbon dioxide is introduced into an appropriate oil reservoir, it swells the oil and reduces its viscosity, improves relative permeability to ease the flow of oil, extracts light crude oil components, and adds solution gas drive energy to the reservoir. All these effects help to recover an additional portion of the original oil that otherwise would be left in the reservoir.

Since September, 1986, Exxon has produced carbon dioxide-rich natural gas from the Madison Limestone at the La Barge anticline (**Figure 4**). Sixty-six percent of this natural gas is carbon dioxide. At Exxon's Shute Creek gas processing plant (**Figure 4**), this carbon dioxide is separated from methane and other gases and is transported by pipeline to Rangley Field in Colorado and to Lost Soldier and Wertz Fields in central Wyoming (**Figure 4**). In these fields, conventional carbon dioxide floods are recovering additional oil. Exxon plans to extend the pipeline from Lost Soldier and Wertz Fields to Hartzog Draw Field in the Powder River Basin (**Figure 4**) so that they can flood the Shannon Sandstone at Hartzog Draw with 160 billion cubic feet of carbon dioxide. The flood is scheduled to begin in 1992 and is expected to recover an additional 14 to 22 million barrels of oil.

Late in 1989, the Enhanced Oil Recovery Institute at the University of Wyoming, in cooperation with Wold Oil Properties, Inc. of Casper, evaluated a single-well, cyclic, carbon dioxide, stimulation process (huff 'n' puff) in Wyoming. The initial test well was the Crooks Gap No. 4 in NW SW sec. 18, T28N, R93W, located in Crooks Gap Field (**Figure 4**). This well produced about 1,600 barrels of incremental oil during two months of production after carbon dioxide injection. Additionally, the Enhanced Oil Recovery Institute used the huff 'n' puff process at wells in Lost Soldier, Wertz, Beaver Creek, Salt Creek, and Little Buffalo Basin fields (**Figure 4**). In Wyoming, the huff 'n' puff process has the potential to be used in thousands of wells that have been abandoned or are currently marginally economic. Amoco Production Company announced plans to use the huff 'n' puff process in as many as 4,164 wells located in Lost Soldier, Wertz, Beaver Creek, Lander, Winkleman, Salt Creek, and Little Buffalo Basin fields (**Figure 4**). Amoco expects to recover as much as an additional 23.6 million barrels of oil from these wells. Conoco plans to test the huff 'n' puff process at a total of six wells in Glenrock South, Sussex West, Gebo, Bonanza and Sunshine North fields (**Figure 4**).

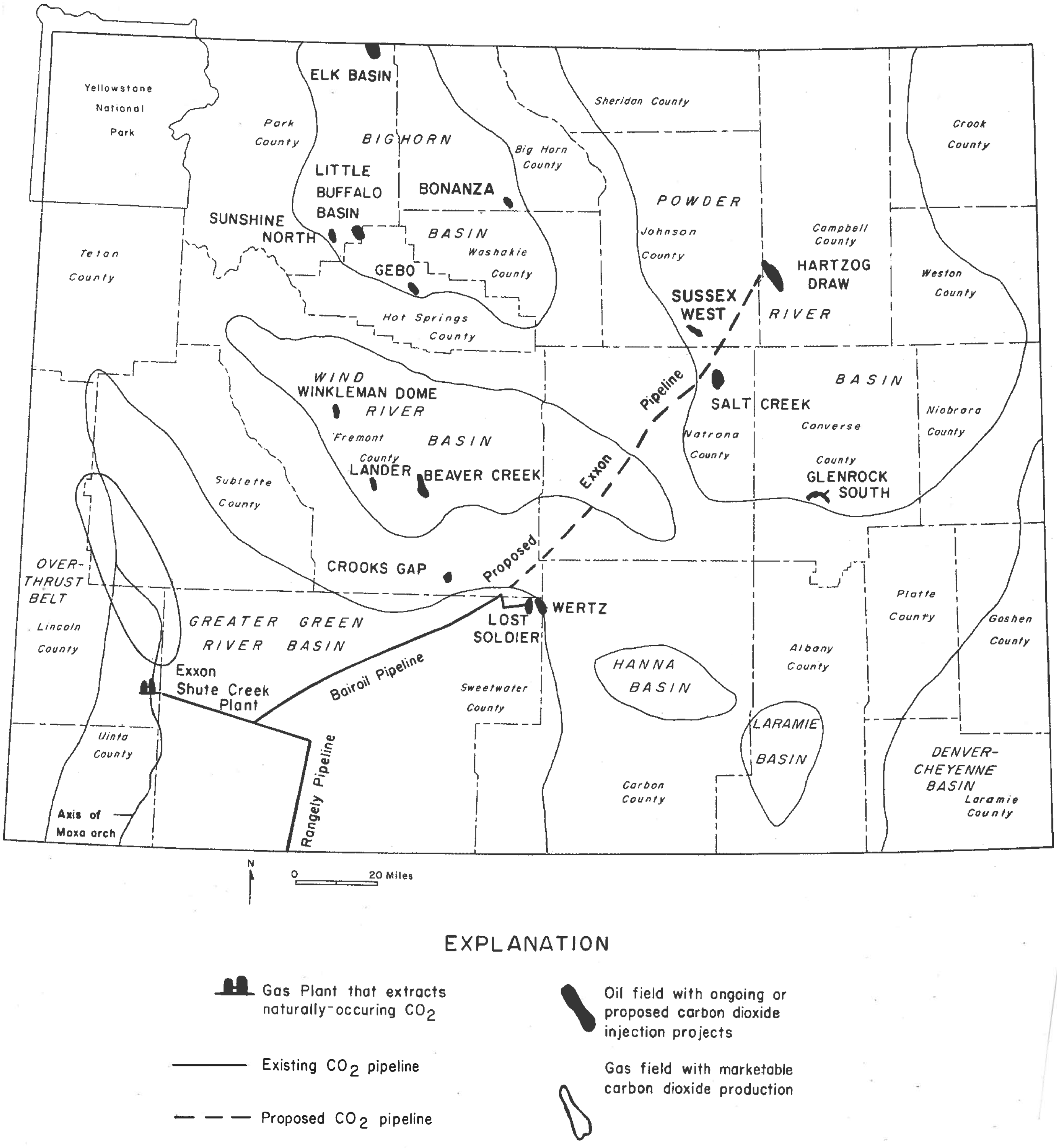



Figure 4. Important fields and facilities in Wyoming related to carbon dioxide production and locations of current and planned enhanced oil recovery operations that use or will use carbon dioxide.

## RESOURCE TERMINOLOGY

Original resources of carbon dioxide are concentrations of this gas that occur naturally in the Earth's crust. Only a part of these resources is currently or potentially economically extractable. Original resources are total in-place resources before any production is subtracted and consist of original identified resources and undiscovered resources.

The following resource terms are modified slightly from the definitions in U.S. Geological Circular 860 (Dolton and others, 1981). The terms defined below are illustrated in **Figure 5**:

*Identified resources* are resources whose location and quantity are known or are estimated from geologic evidence.

*Remaining identified resources* are equal to original identified resources minus any production. This resource category includes recoverable identified resources (reserves) and marginally economic and subeconomic identified resources.

*Undiscovered resources* are resources outside of known fields and are estimated from broad geologic knowledge and theory. This resource category is the most speculative of all resource categories.

*Undiscovered recoverable resources* are resources that would be economically extractable once they are discovered. These resources equate to the Potential Gas Committee's (1989) most likely possible resources.

*Undiscovered marginal and subeconomic resources* would be unrecoverable under present technologic and/or economic conditions, but part of the resources may become recoverable if conditions change.

*Remaining recoverable resources* include remaining recoverable identified resources and recoverable undiscovered resources. Remaining recoverable identified resources equal the total of measured, indicated, and inferred resources and are the same as reserves.

## ORIGINAL AND REMAINING IDENTIFIED CARBON DIOXIDE RESOURCES

### Methodology

The volume of original identified carbon dioxide in each of the major reservoirs was calculated by the following reservoir equation (modified from Vance, 1950):

$$V = \frac{1}{10^{12}}(A)(H)\,\frac{43{,}560\ \text{ft}^3}{\text{acre-foot}}\,(Pe)(Sg)\,\frac{P}{14.73\ \text{lb/in}^2}\,\frac{520°R}{T}\,\frac{1}{Z}\,(C)$$

where

| | | |
|---|---|---|
| V | = | volume of carbon dioxide in place (trillions of cubic feet) |
| A | = | areal extent of gas-bearing reservoir in acres |
| H | = | average thickness of reservoir rocks in feet |
| Pe | = | average effective porosity expressed as a decimal |
| Sg | = | average gas saturation expressed as a decimal |
| P | = | average reservoir pressure in pounds per square inch |
| °R | = | degrees Rankine |
| T | = | average reservoir temperature in degrees Rankine = 460° +F° |
| Z | = | average gas compressibility |
| C | = | average carbon dioxide concentration expressed as a decimal |

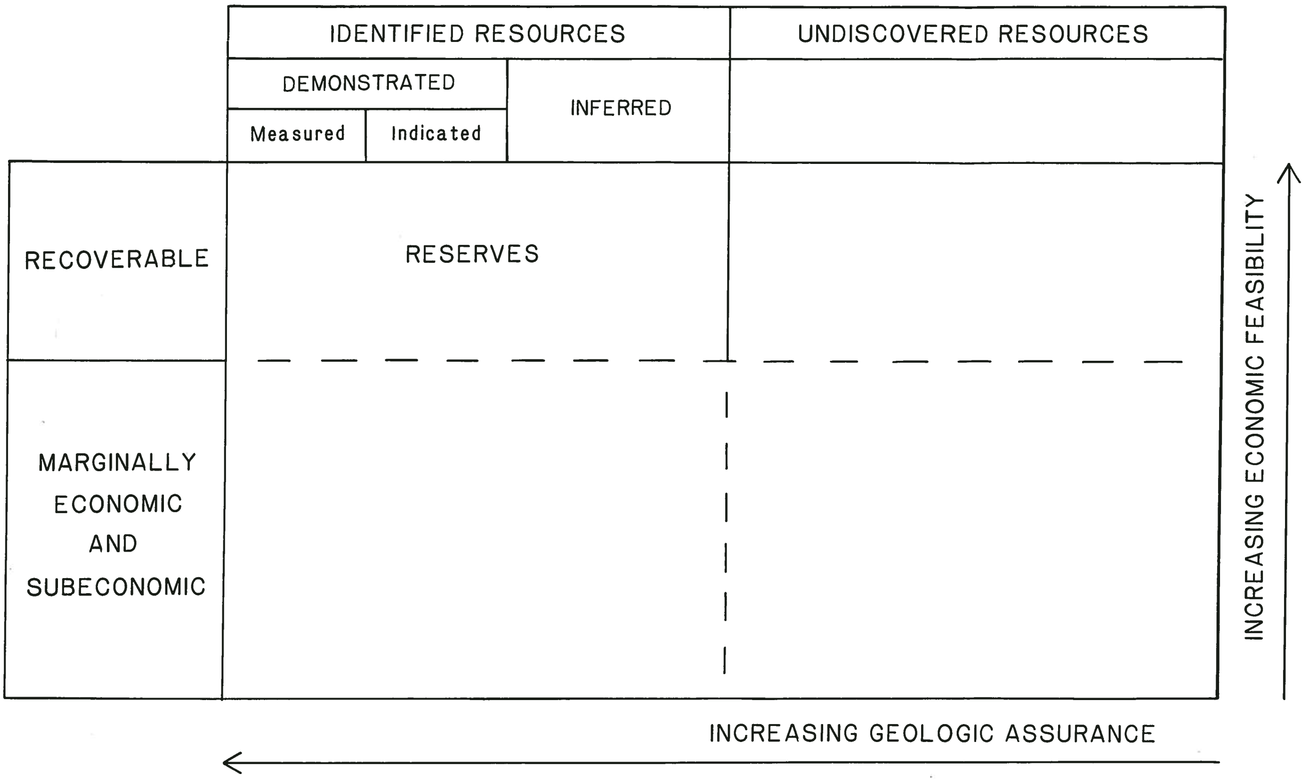



Figure 5. Diagrammatic representation of carbon dioxide resource classification for Wyoming (modified from Dolton and others, 1981).

This equation is based on the assumptions that the carbon dioxide volume in a reservoir is a function of the reservoir's areal extent, average thickness, average porosity, average gas saturation, average pressure and temperature, average gas compressibility, and average carbon dioxide concentration.

Since the natural gases in the reservoirs that were assessed contain a high percentage of nitrogen, hydrogen sulfide, and helium, as well as carbon dioxide, a procedure proposed by Wichert and Aziz (1972) was used to adjust the critical properties (temperature and pressure) of the gas. The adjusted critical properties were used to calculate the reduced properties (temperature and pressure), which determine the gas-compressibility factor (Z-factor).

In most cases, the reservoir data that were necessary to calculate the volume of original identified carbon dioxide were available from various published sources. Where reservoir data were unavailable, the data were estimated from geologic analogs. A summary of the reservoir parameters used for various areas and formations appears in **Table 1**.

## La Barge anticline

Most of the remaining identified resources of carbon dioxide in Wyoming occur within the Madison Limestone in La Barge anticline on the northern end of the Moxa arch in the western Greater Green River Basin (**Figure 1**). The Madison Limestone has over 4,000 feet of closure down to the inferred gas/water contact at La Barge anticline (**Figure 6**). The areal extent of this reservoir is over 1,000 square miles (based on a limited number of wells). Seismic data indicate that a reverse fault limits the reservoir on the west (D.L. Blackstone, Jr., personal communication, 1990).

The reservoir is probably continuous across the anticline (Stilwell, 1989). The Madison is over 800 feet thick on the crest of the anticline and thins slightly to the south. The Madison is mainly an alternating sequence of gray fossiliferous limestone and gray, finely crystalline dolomite. Dolomite is the dominant rock type and commonly has porosity of six percent while the limestone is generally less porous. Because a large portion of the Madison is usually perforated in a production well, an average reservoir thickness of 400 feet was used to calculate resources in the Madison for this anticline. Carbon dioxide in the gas from wells at La Barge averages around 66 percent near the crest of the anticline and increases structurally lower on the anticline. The 1 Amoco/Keller Rubow well on the southern end of the anticline tested gas that contained 95 percent carbon dioxide; this well also established the apparent gas/water contact. An average carbon dioxide composition of 70 percent was used to calculate resources for the Madison on the La Barge anticline.

Based on the reservoir parameters in **Table 1**, original identified resources of carbon dioxide in the Madison reservoir at La Barge anticline were 111.76 trillion cubic feet. Since production of carbon dioxide from this reservoir (through December 31, 1990) was an estimated 0.50 trillion cubic feet, the remaining identified resources are 111.26 trillion cubic feet (**Table 2**).

Other reservoirs at La Barge anticline are also capable of producing significant quantities of carbon dioxide gas. The Bighorn Dolomite was tested in five wells and each test recovered high gas volumes that averaged 85 percent carbon dioxide. Porosity development in the Bighorn is fairly good, although the potential reservoir in the Bighorn is much thinner than in the Madison. All five test wells are near the crest of the anticline and there is very little information away from the crest. The lack of data resulted in a much smaller estimate of original identified carbon dioxide resources for the Bighorn than for the Madison. Reservoir parameters (**Table 1** ) were used to estimate 5.28 trillion cubic feet of original identified carbon dioxide resources in the Bighorn Dolomite. Since carbon dioxide production from the Bighorn has been negligible, remaining identified resources also total 5.28 trillion cubic feet (**Table 2**).

The Tensleep Sandstone has been tested in four wells on the La Barge anticline. Two of the tests recovered fairly high volumes of gas with an average carbon dioxide content of 64 percent while the other two tests recovered only a trace of gas. The Tensleep reservoir is discontinuous and only 50 feet of the formation is considered productive. The original and remaining identified resources of carbon dioxide for the Tensleep, based on its reservoir parameters (**Table 1**), are estimated at 0.38 trillion cubic feet each (**Table 2**).

Three wells in the Phosphoria Formation tested fairly high gas-flow rates. Tests in two other wells recovered only traces of gas. Average carbon dioxide content of the gas is 63 percent. Porosity development is sporadic and the average reservoir thickness is 50 feet. The reservoir parameters for the Phosphoria (**Table 1**) yield an estimated original and remaining identified carbon dioxide resource of 0.39 trillion cubic feet each (**Table 2**).

Gas in the Darby Formation was tested from one well at La Barge. The reservoir in this well is relatively thin and porosity is low. The Darby lacks good reservoir characteristics (**Table 1**). The U.S. Bureau of Mines analyzed gas from one Darby well: the gas averaged 67 percent carbon dioxide (Moore and Sigler, 1987a). Original and remaining identified resources of carbon dioxide assigned to the Darby at La Barge anticline are estimated at 0.07 trillion cubic feet each (**Table 2**).

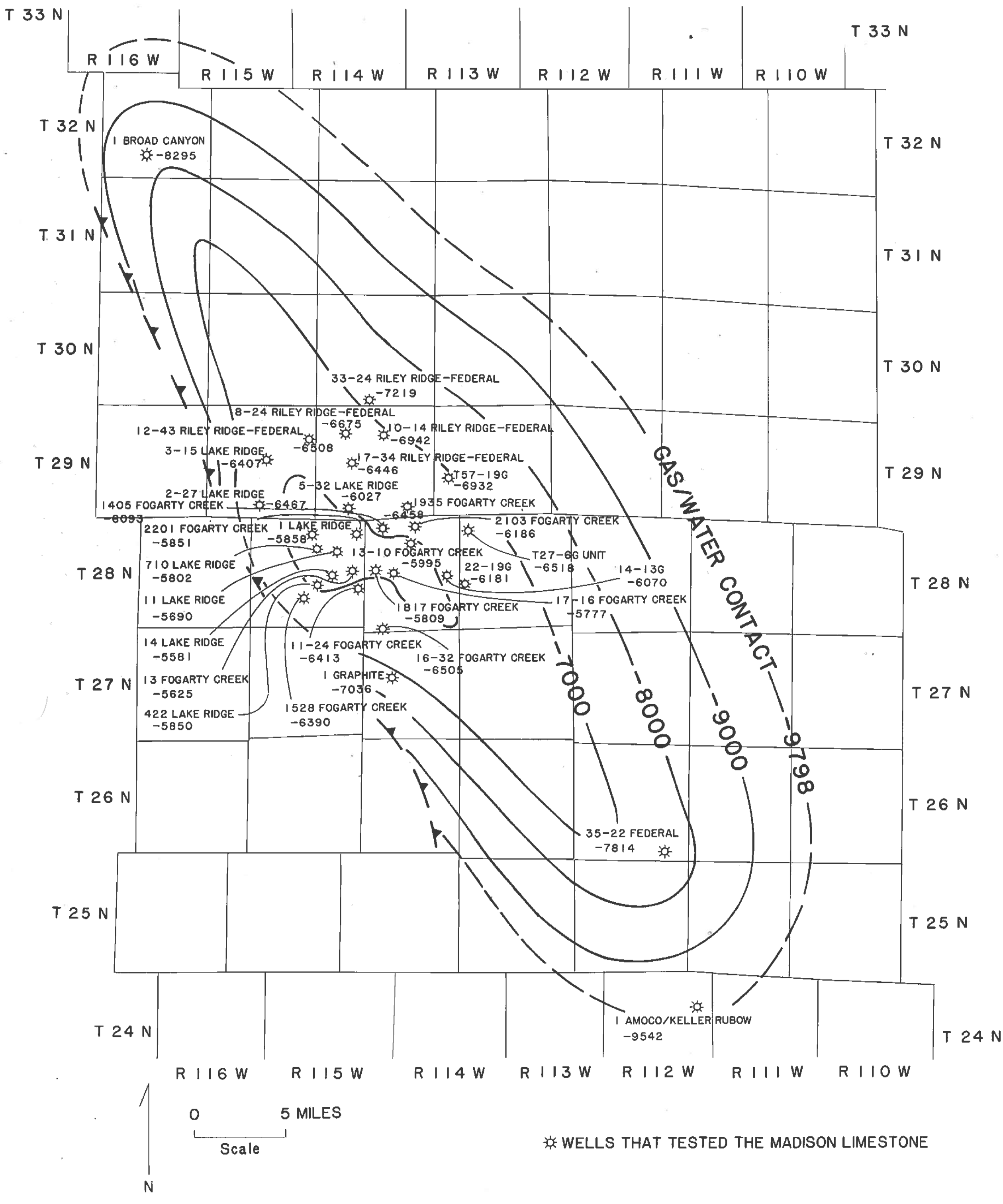



Figure 6. Structure contour map drawn on the top of the Madison Limestone at La Barge anticline (modified after Stilwell, 1989).

Table 2. Remaining identified resources of carbon dioxide in Wyoming by field and formation[1,2].

| Field | Formation | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Madison Limestone | Bighorn Dolomite | Tensleep Sandstone | Phosphoria Formation | Weber Sandstone | Morgan Formation | Nugget Sandstone | Darby Formation | Total |
| La Barge | 111.26 | 5.28 | 0.38 | 0.39 | | | | 0.07 | 117.38 |
| Bruff | 0.43 | | | | | | | | 0.43 |
| Church Buttes | 1.89 | | | | | 0.22 | | | 2.11 |
| Butcher Knife Springs | | | | | | 0.01 | | | 0.01 |
| Whitney Canyon-Carter Creek | 0.14 | | | | | | | | 0.14 |
| Table Rock | 0.37 | | | | 0.04 | | | | 0.41 |
| Brady | | | | | 0.19 | | 0.44 | | 0.63 |
| Madden | 0.95 | | | | | | | | 0.95 |
| Total | 115.04 | 5.28 | 0.38 | 0.39 | 0.23 | 0.23 | 0.44 | 0.07 | 122.06 |

[1]All volumes are in trillions of cubic feet.
[2] Resources remaining after December 31, 1990.

The original identified carbon dioxide resources for the Madison, Bighorn, Tensleep, Phosphoria, and Darby reservoirs at La Barge anticline are an estimated 117.88 trillion cubic feet (**Table 3**). Over 94 percent of these resources are in the Madison Limestone. The remaining identified resources at La Barge are an estimated 117.38 trillion cubic feet (**Table 2**).

## Southern Moxa arch

There are additional identified carbon dioxide resources in the Madison Limestone at Bruff Field, in the Madison Limestone and Morgan Formation at Church Buttes Field, and in the Morgan Formation at Butcher Knife Springs Field. All three of these fields are on the southern end of the Moxa arch in the western Greater Green River Basin (**Figure 1**).

Gas from the Madison at Bruff Field was sampled by the U.S. Bureau of Mines (Moore and Sigler, 1987a) at one well from two different intervals below a depth of 17,000 feet. The gas averaged 83 percent carbon dioxide, however, flow rates were fairly low. Porosity development and reservoir quality are not as good as at La Barge and acid stimulation may be necessary to initiate production. The reservoir parameters for the Madison at Bruff Field (**Table 1**) yield an estimated original remaining and identified carbon dioxide resource of 0.4 3 trillion cubic feet each (**Table 2**).

Gas from two different wells in the Madison Limestone in Church Buttes Field was analyzed for carbon dioxide (Moore and Sigler, 1987a). The carbon dioxide content for the two wells averaged 86 percent. Test flow rates for both wells were over 10 million cubic feet of gas per day. The Madison is below a depth of 18,000 feet in this area. Based on reservoir parameters (**Table 1**) for the Madison at Church Buttes, the estimated original remaining and identified carbon dioxide resources are 1.89 trillion cubic feet each (**Table 2**).

The Morgan Formation is capable of carbon dioxide production at Church Buttes and Butcher Knife Springs Fields. Test flow rates from two wells at Church Buttes Field averaged nearly four million cubic feet per day and the flow rates from five wells at Butcher Knife Springs Field were from 2.6 to 6.0 million cubic feet per day. The carbon dioxide contents of the gases at both fields, which are low when compared to the reservoirs that were discussed previously, average 24 percent at Church Buttes Field and 22 percent at Butcher Knife Springs Field (Curry, 1979; Golden, 1979; Moore and Sigler, 1987a). The relatively low carbon dioxide contents and fairly thin reservoirs (**Table 1**) combine to limit carbon dioxide resources in the Morgan at these two fields. The Morgan at Church Buttes Field has an estimated original and remaining identified resource of 0.22 trillion cubic feet each; at Butcher Knife Springs Field the estimated original and remaining identified resources are only 0.01 trillion cubic feet each (**Table 2**).

## Overthrust Belt

The Madison Limestone at Whitney Canyon-Carter Creek Field (**Figure 1**) contains several trillion cubic feet of gas. Even though the gas from the Madison at this field contains only six percent carbon dioxide (Ver Ploeg and De Bruin, 1982), the Madison has a thick pay zone with good porosity (Hoffman and Kelly, 1981) developed over a large area (**Table 1**). The Madison at Whitney Canyon-Carter Creek has an estimated original identified carbon dioxide resource of 0.19 trillion cubic feet (**Table 3**) based on its reservoir parameters (**Table 1**). Production of carbon dioxide from the Madison at this field (through December 31, 1990) is an estimated 0.05 trillion cubic feet. Remaining identified resources are 0.14 trillion cubic feet (**Table 2**).

## Eastern Greater Green River Basin

Gas from three wells in the Madison Limestone at Table Rock Field (**Figure 1**) was analyzed for carbon dioxide content (Moore and Sigler, 1987a). The gas averaged 16 percent carbon dioxide and test flow rates were from 6.8 to 20 million cubic feet of gas per day from zones below a depth of 18,000 feet. The estimated original and remaining identified carbon dioxide resources of the Madison at Table Rock Field are 0.37 trillion cubic feet each (**Table 2**) based on the reservoir parameters from **Table 1**.

The Weber Sandstone is capable of carbon dioxide production at Table Rock (Colburn, 1979) and Brady (Nicolaysen, 1979a; 1979b) fields (**Figure 1**). The average carbon dioxide content of gas from the Weber averages 10 percent at Table Rock Field (Moore and Sigler, 1987a) and 27 percent at Brady Field (Moore and Sigler, 1987a). The relatively low carbon dioxide content of the gas from these two reservoirs limits the resources. Based on the reservoir parameters (**Table 1**), there are an estimated 0.25 trillion cubic feet of original identified carbon dioxide resources in the Weber at Brady Field and only 0.04 trillion cubic feet in the Weber at Table Rock Field. Production of carbon dioxide from the Weber at Brady Field (through December 31, 1990) was an estimated 0.06 trillion cubic feet and remaining identified resources are 0.19 trillion cubic feet (**Table 2**). There are an estimated 0.04 trillion cubic feet of remaining identified carbon dioxide resources in the Weber at Table Rock Field (**Table 2**).

Natural gas from four wells in the Nugget Sandstone at Brady Field was analyzed for carbon dioxide content by the U.S. Bureau of Mines (Moore and Sigler, 1987a). The average carbon dioxide concentration for the gas from these four wells is 72 percent. Estimated original identified resources of carbon dioxide in the Nugget at Brady Field are 0.46 trillion cubic feet based on the reservoir parameters from **Table 1**. Production of carbon dioxide from the Nugget at Brady Field (through December 31, 1990) was an estimated 0.02 trillion cubic feet. Remaining identified resources are 0.44 trillion cubic feet (**Table 2**). **Table 3** summarizes the resources at each of the fields discussed above.

Table 3. Identified resources at fields with major carbon dioxide accumulations[1].

| | Original | Cumulative production[2] | Remaining[3] | Remaining recoverable[3] | Remaining Marginal and subeconomic[3] |
|---|---|---|---|---|---|
| La Barge | 117.88 | 0.50 | 117.38 | 58.440 | 58.940 |
| Church Buttes | 2.11 | | 2.11 | 1.055 | 1.055 |
| Bruff | 0.43 | | 0.43 | 0.215 | 0.215 |
| Butcher Knife Springs | 0.01 | | 0.01 | 0.005 | 0.005 |
| Whitney Canyon-Carter Creek | 0.19 | 0.05 | 0.14 | 0.045 | 0.095 |
| Table Rock | 0.41 | | 0.41 | 0.205 | 0.205 |
| Brady | 0.71 | 0.08 | 0.63 | 0.275 | 0.355 |
| Madden | 0.95 | | 0.95 | 0.475 | 0.475 |
| Total | 122.69 | 0.63 | 122.06 | 60.715 | 61.345 |

[1] All volumes are in trillions of cubic feet.
[2] Production through December 31, 1990.
[3] Resources remaining after December 31, 1990.

### Wind River Basin

Two wells have penetrated the Madison Limestone at Madden anticline on the northern margin of the Wind River Basin (**Figure 1**). Both wells were completed in the Madison below a depth of 23,000 feet (Brown and Shannon, 1989a). Log correlations suggest that porosity in the Madison is developed across the entire Madden structure (Brown and Shannon, 1989b). Carbon dioxide content averages 17 percent at the two wells and the estimated original and remaining identified resources are each 0.95 trillion cubic feet (**Tables 2** and **3**) based on the Madison Limestone's reservoir parameters (**Table 1**).

## UNDISCOVERED CARBON DIOXIDE RESOURCES

The preliminary estimate of undiscovered carbon dioxide resources in this report was derived from the Potential Gas Committee's (1989) estimate of the most likely possible resources of methane in reservoirs between depths of 15,000 and 30,000 feet in the Greater Green River Basin. They estimated that resource at 15.60 trillion cubic feet of methane. The Potential Gas Committee's most likely possible resources are those recoverable undiscovered resources that are expected from new discoveries associated with a productive formation in a productive geologic province.

Methane associated with low-Btu gas in Paleozoic reservoirs comprises a large part of the Potential Gas Committee's (1989) most likely estimate of possible resources between depths of 15,000 and 30,000 feet in the Greater Green River Basin. The Potential Gas Committee's estimates are based on factors that control known occurrences of natural gas discovered in the same or a similar geologic province. Those factors are then compared with the factors present in prospective areas. The factors are: 1) the existence of source rocks, 2) the maturation of organic material within those source rocks, 3) the presence of reservoir rocks, and 4) the existence of traps. The estimates are derived by multiplying the volume of potential gas-bearing reservoir rocks by a yield factor. The yield factor is discounted for low probabilities that the accumulations and/or traps exist. Yield factors are calculated with data from known gas accumulations that are considered most similar to the one being evaluated. The yield factor is cumulative production plus proved reserves divided by the volume of reservoir rock. The factor is adjusted for variations applicable to the prospective area (Potential Gas Committee, 1989).

Based on the above discussion and the following assumptions, undiscovered carbon dioxide resources in the State are an estimated 31.20 trillion cubic feet. It was assumed that there is as much carbon dioxide as methane in the low-Btu gas that dominates the Potential Gas Committee's most likely possible resources (recoverable undiscovered resources) of 15.60 trillion cubic feet in the Greater Green River Basin. Another assumption is that there is twice as much in-place carbon dioxide as there is recoverable carbon dioxide Consequently, the undiscovered resources of carbon dioxide will be twice as large as the Potential Gas Committee's estimate of possible resources. It was also assumed that although carbon dioxide will be discovered in other parts of the State, it is unlikely that concentrations will be high enough or that reservoirs will be large enough to contribute significant amounts of carbon dioxide to undiscovered resources in Wyoming. Consequently, the estimated undiscovered resources in the Greater Green River Basin comprise the estimate for the whole State.

## REMAINING RECOVERABLE CARBON DIOXIDE RESOURCES (THROUGH DECEMBER 31, 1990)

Through 1990, approximately 0.63 trillion cubic feet of carbon dioxide have been produced in Wyoming and most of that production came from the Madison Limestone at La Barge. This leaves Wyoming with a remaining recoverable resource of 76.315 trillion cubic feet. Of this, 60.715 trillion cubic feet is identified and 15.60 is undiscovered. The current rate of production is 127 billion cubic feet per year. Another 1,000 to 2,000 wells would have to be drilled at La Barge anticline alone to recover most of the remaining recoverable resources. Currently, carbon dioxide production at La Barge comes from only 15 wells.

## SUMMARY

Wyoming's original resources of carbon dioxide were an estimated 153.89 trillion cubic feet and can be subdivided into 122.69 trillion cubic feet of original identified resources and 31.20 trillion cubic feet of undiscovered resources (**Table 4**). Approximately 0.63 trillion cubic feet of carbon dioxide have been produced in the State (**Table 5**). Most of that production came from 15 wells in the Madison Limestone at La Barge anticline. After production of 0.63 trillion cubic feet is subtracted, Wyoming has remaining carbon dioxide resources of 153.26 trillion cubic feet (through December 31, 1990) (**Table 4**).

Table 4. Original and remaining resources of carbon dioxide in Wyoming[1].

| | Identified | | Undiscovered | Total | |
|---|---|---|---|---|---|
| | Original | Remaining[2] | Remaining[2,3] | Original | Remaining[2] |
| Recoverable | 61.345 | 60.715 | 15.60 | 76.945 | 76.315 |
| Marginal and Subeconomic | 61.345 | 61.345 | 15.60 | 76.945 | 76.945 |
| Total | 122.69 | 122.06 | 31.20 | 153.89 | 153.26 |

[1]All volumes are in trillions of cubic feet.
[2] Resources remaining after December 31, 1990.
[3]In this case remaining resources are the same as original resources.

Table 5. Cumulative production of carbon dioxide from reservoirs in Wyoming fields[1,2].

| Field | Reservoir | Production |
|---|---|---|
| La Barge | Madison Limestone | 0.50 |
| Whitney Canyon-Carter Creek | Madison Limestone | 0.05 |
| Brady | Weber Sandstone | 0.06 |
| Brady | Nugget Sandstone | 0.02 |
| Total | | 0.63 |

[1]All volumes are in trillions of cubic feet.
[2] Resources remaining after December 31, 1990.

Remaining identified resources of carbon dioxide in Wyoming (through December 31, 1990) are estimated at 122.06 trillion cubic feet (**Table 3**). The La Barge anticline contains most of these resources (117.38 trillion cubic feet) in the Madison Limestone, Bighorn Dolomite, Tensleep Sandstone, Phosphoria Formation, and the Darby Formation (**Table 2**). Over 94 percent of the remaining resources (111.26 trillion cubic feet) at La Barge anticline are in the Madison Limestone.

Other fields also contain carbon dioxide, although none have resources that even approach those at La Barge anticline. Bruff, Church Buttes, Butcher Knife Springs, Table Rock, and Brady Fields in the Greater Green River Basin, Whitney Canyon-Carter Creek Field in the Overthrust Belt, and Madden anticline in the Wind River Basin have remaining identified carbon dioxide resources which total 4.68 trillion cubic feet. The Madison Limestone in these fields contains 3.78 trillion cubic feet of this total (**Table 2**).

Remaining recoverable identified resources are an estimated 60.715 trillion cubic feet (**Figure 7, Table 4**). Marginal and subeconomic identified resources are an estimated 61.345 trillion cubic feet (**Figure 7, Table 4**).

Wyoming also has an estimated 15.60 trillion cubic feet of undiscovered recoverable carbon dioxide resources and an equal amount of marginal and subeconomic undiscovered resources (**Figure 7, Table 4**). Paleozoic formations below a depth of 15,000 feet in the Greater Green River Basin will contain most of these undiscovered resources.

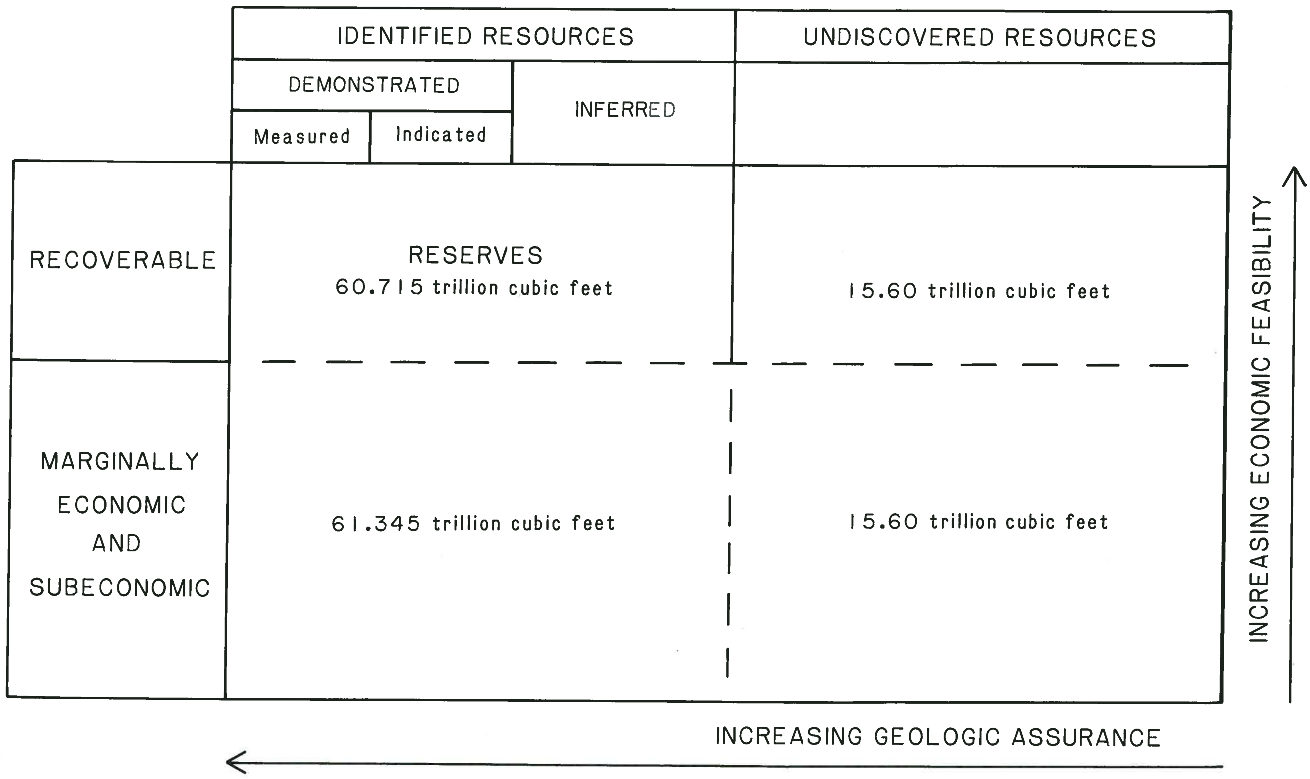



Figure 7. Diagrammatic representation of remaining carbon dioxide resources in Wyoming showing resource amount by category. Total remaining resources are 153.26 trillion cubic feet through December 31, 1990 (modified from Dolton and others, 1981).

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