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# Exploration Opportunities in the Greater Rocky Mountain Region, Central Western, U.S.A.

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## ABSTRACT

The Greater Rocky Mountain Region covers approximately 1/5 of the contiguous 48 states. The United States Geologic Survey recognizes 22 "provinces" or "areas" in the Region: 18 are productive of oil or gas. They estimate that 10.4 BB oil and condensate and 259.8 TCFG remain to be discovered.

Known source and reservoir rocks extend throughout a thick sedimentary section ranging from Pre-Cambrian to Tertiary in age. Virtually every conceivable type of tectonic and sedimentary environment known is present in some area of the Region. Additional oil production from established plays is not expected to be large. Greatest potential exists in unconventional plays and in sparsely drilled deeper sections of individual basins.

Gas will be more important than oil. Most of the gas potential is related to sources in coal-bearing Cretaceous and Tertiary sediments. Much of this gas will be found in coal bed reservoirs or in low-permeability sandstones. The deeper and less-explored parts of many basins will contain gas because of advanced thermal maturity.

Much of the potential production will fall in the middle and lower ranges of "Masters' Resource Triangle", which in the case of the Rocky Mountain Region has a broader base than many other areas of the world. Exploration and development will be greatly influenced by technical, economic and political factors. Examples of recent significant discoveries that may serve as analogs for the future will be presented. Many of these "discoveries" are unconventional accumulations and have resulted from the application of new technology to areas of previously abandoned or non-/sub-commercial wells.

## INTRODUCTION

The Greater Rocky Mountain Region (the "Rocky Mountain Region", "Region", or GRMR) is located in the central western part of the contiguous 48 States of the United States of America (Figure 1). It extends north-south from the Canadian to the Mexican borders (1000 mi; 1600 km) and east-west from the northern Great Plains to the central Great Basin (800 mi; 1290 km) and contains about 1/5 of the total contiguous 48 states land area. It incorporates all or parts of the States of Idaho, Montana, North Dakota, South Dakota, Wyoming, Utah, Nevada, Nebraska, Colorado, New Mexico and Arizona.

Exploration potential for the Region was last published in a "province-type" assessment by the American Association of Petroleum Geologists (AAPG) in Memoir 15 : "Future Petroleum Provinces of the United States —Their Geology and Potential" (Cram, 1971). This memoir contained detailed papers on fifteen separate geologic provinces and three regional summary papers contributed by eighteen authors. Most of the basic geology considered in the papers is still pertinent; however, since 1971, thousands of wells have been completed, hundreds of fields have been discovered that contain several billion barrels of oil and trillions of cubic feet of gas, and numerous papers have been written concerning various parts of the Region. Better understanding has also been obtained considering such subjects as the occurrence of source rocks, what constitutes a viable reservoir, what petroleum systems are present and how they operate, and subtleties of structure. Great progress has also been made in geophysics, logging, drilling and completion techniques. These have a significant impact on establishing a new and larger potential resource base. This paper attempts to update current knowledge on the exploration/development potential of this vast and geologically heterogeneous region. It must necessarily be an overview biased by the authors' knowledge, experience and interest. Every geoscientist working in the Region has ideas on what is important in characterizing an area or a prospect, where the next prospect or significant play is going to be made, and what its potential is. Collectively, this is a powerful force for new exploration and it is impossible to predict what discoveries in both technology and actual fields will be made in the future. The best we can do is assess what we now know and project the use of this knowledge into a future trend.

## HISTORY AND RESOURCE ESTIMATION

The Region has a long history of oil and gas production commencing with drilling in 1878 and the establishment of production at Florence Oil Field in 1881. This field lies within the Canyon City Depression, a small sub-basin near the southwest corner of the Denver Basin (Kupfer, 1999). Although not recognized at the time, Florence field, which produces from a fractured shale reservoir associated with a mature source rock is in a synclinal position, and was the first of the "deep basin" or "basin center"-type oil accumulations that are characteristic of many subsequently discovered and prospective accumulations in other Rocky Mountain basins.

Since initial production in 1881, hundreds of significant oil and gas fields have been discovered in a wide variety of structural and stratigraphic settings (Figure 1). These include at least 7 super-giant fields with known resources of greater than 500 million barrels of oil or oil- equivalent (Carmalt and St. John, 1986). The United States Geological Survey (USGS, 1997) has divided the Region into 22 provinces (see Figure 2 and Appendix Figure A1 and Table A1). Eighteen of these provinces are currently productive of oil and gas and were credited with an estimated median-value *known resources* of 17 billion barrels (BB) of petroleum liquids (PL) consisting of oil (O) and natural gas liquids (NGL) and 80 trillion cubic feet of gas (TCFG) in their 1997 assessment (Appendix, Table A2). These values represented 8.5% of U.S. oil and 8.8% of gas.

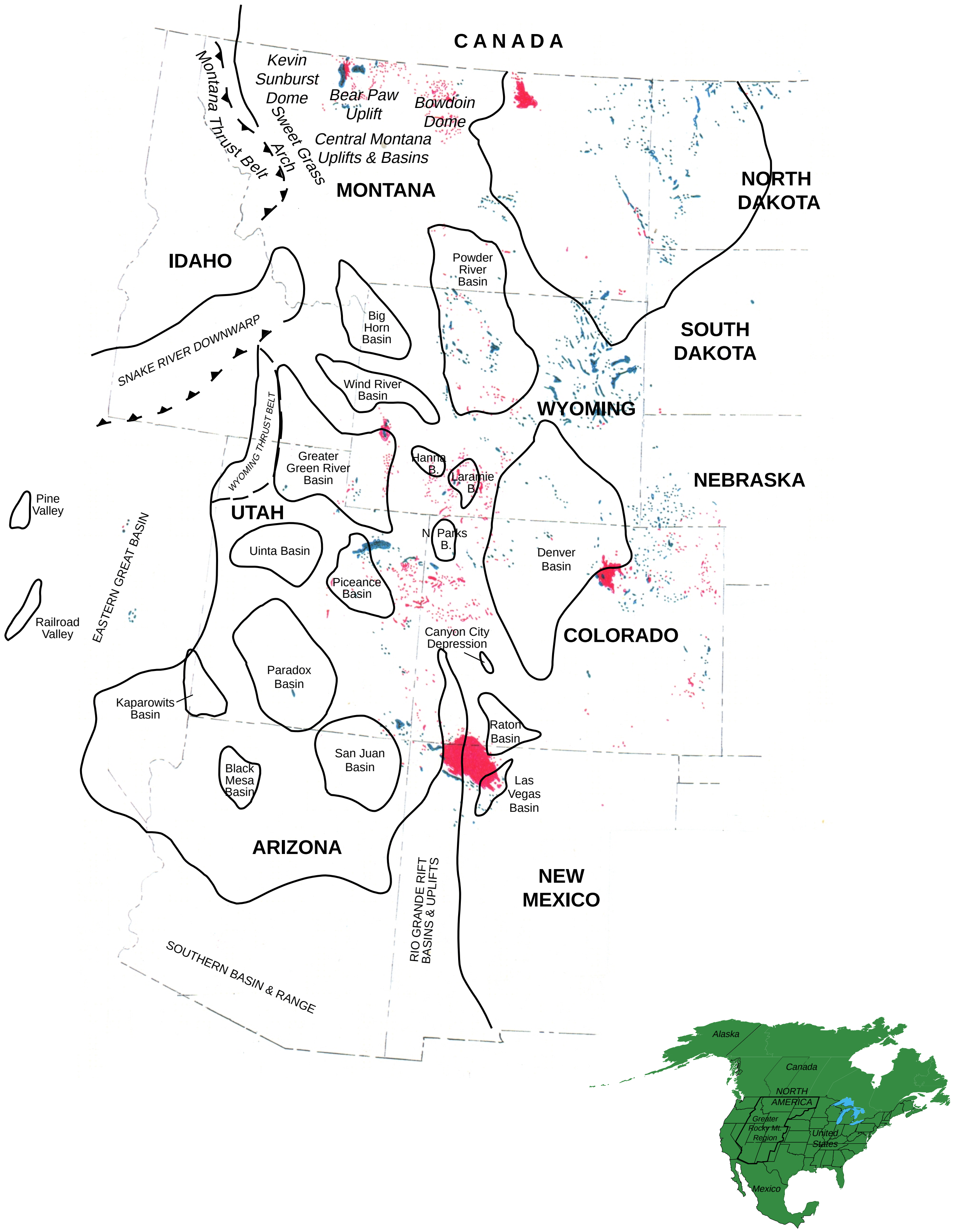



Figure 1. Maps showing location of the Greater Rocky Mountain Region and distribution of oil and gas fields.

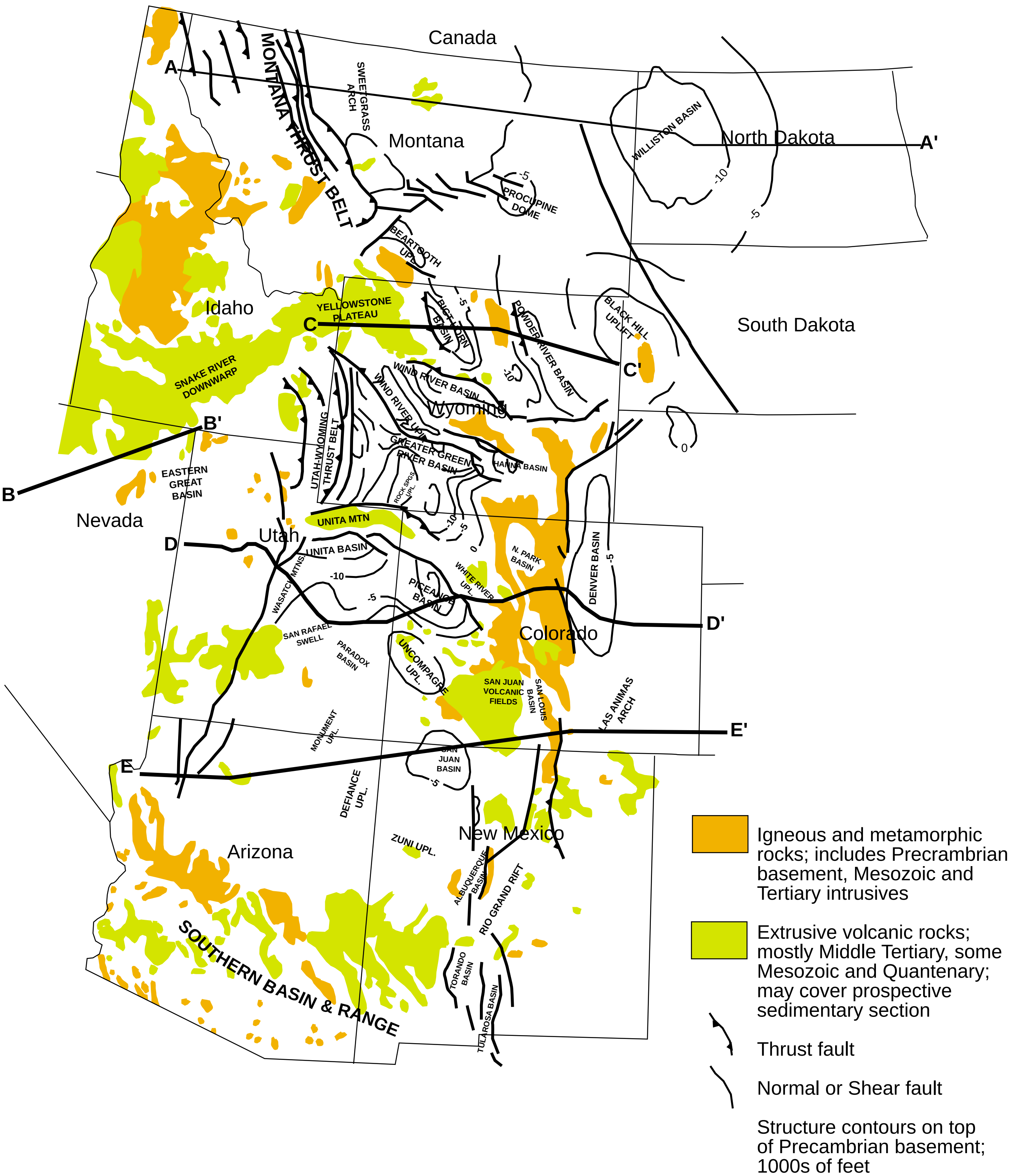



Figure 2. Geologic map of the Greater Rocky Mountain Region showing a) areas of igneous or metamorphic basement and surface volcanic cover, b) structure contours at the base of the sedimentary secion and c) location of cross sections depicted in Figure 3.

TABLE 1
SUMMARY OF POTENTIAL RESOURCE ESTIMATES

| | AUTHORITY | | | | | | |
|---|---|---|---|---|---|---|---|
| | AAPG* | USGS** | | PGA*** | GRI | | TYLER |
| | OIL | OIL+NGL | GAS | | | | |
| RESOURCE CATEGORY | BB | | TCF | | | | |
| "Conventional" | 15.40 | 7.61 | 0.53 | | | | |
| "Traditional" | | | | 150.02 | | | |
| "Continuous"—Ss, Frac Sh, Chalk | | 2.81 | 203.85 | | | | |
| Coalbed Methane | | | 25.44 | 41.72 | 38.92** | 477**** | 534**** |
| TOTALS: | 15.40 | 10.42 | 259.82 | 191.74 | | | |

* Median value, economically recoverable undiscovered conventional resource, (excluding the Pedragosa Basin, SW New Mexico)
** Median value of technically recoverable resources
*** Mean value by statistical aggregation of probable, possible and speculative economically and technically recoverable resources
**** In-place resource. Includes deeply buried coals that may not be producible at the present state of technology due to absence of open cleats that provide permeability

SOURCES: AAPG "Expert Panel", 1992; USGS, 1995; PGA, 1999; GRI, 1999; TBEG (Tyler, et al), 1999

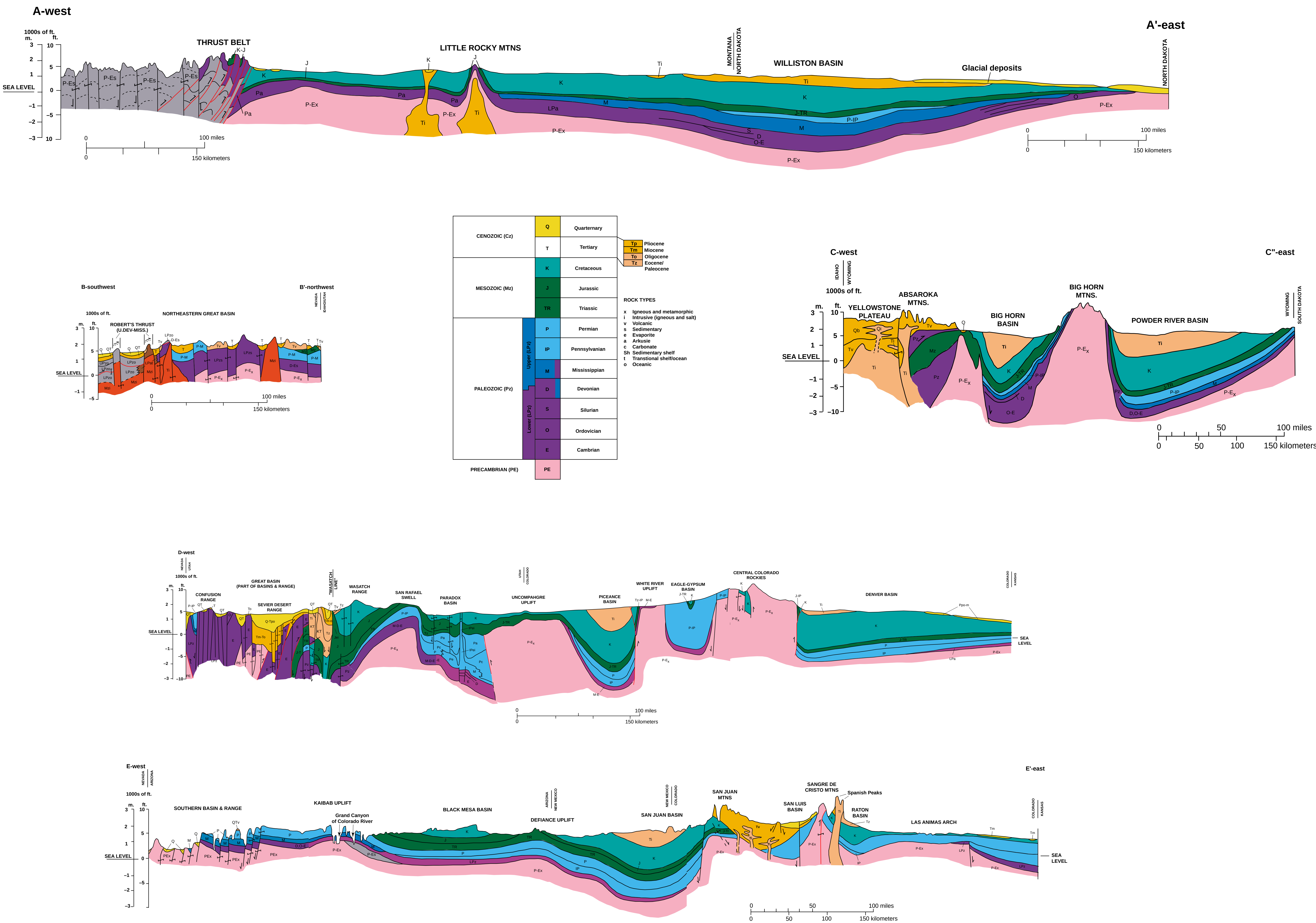
Since estimates of *future resources* in the Greater Rocky Mountain Region were presented in Memoir 25 (Ambrose, 1971; Curry, 1971) a number of entities have made estimates of future oil and gas discoveries and developments. The most recent of these include studies made by the USGS (1995), the Potential Gas Committee (1999) of the Potential Gas Agency (PGA), the Gas Research Institute (GRI) (1999), and others investigating the total in-place volume of coalbed methane (Tyler and others, 1997). A generalized summary of conclusions reached in these studies is presented in Table 1. The conclusions are supported by more-detailed summaries presented for individual geologic areas in the Appendix. Table 1 also includes results of an assessment made by an AAPG “panel of experts”.

The categories and estimates made by the various entities are not all compatible. They use different categories and different time frames. However the bottom line estimates should serve as a guide for an appreciation of target size. All of the estimates indicate that a substantial amount of oil and gas remains to be found in the Region. The importance of gas in the estimates is obvious. According to the most recent Potential Gas Agency (PG) estimates, 24.4% of future additions to gas reserves in the lower 48 states will come from the GRMR. The 1992 estimate made by the AAPG “expert panel” predicts a larger volume of oil than the 1995 USGS estimate. This may reflect more intimate practical knowledge of the Region and of the impact of new technology, as well as a higher degree of optimism on the part of qualified oil and gas industry scientists.

## GEOLOGIC FRAMEWORK

A generalized geologic map of the Greater Rocky Mountain Region is contained in Figure 2. Five simplified east-west cross sections through representative parts of the Region are presented in Figure 3. The geologic map shows 1) structural contours at the base of the sedimentary section, 2) areas of exposed igneous or metamorphic rocks, 3) extrusive volcanic rocks that may be underlain by a sedimentary section and 4) names of key basins and uplifts.

Figure 3. Cross sections through the Greater Rocky Mountain Region. (Simplified from sections contained in the AAPG Highway Map Series)



With a few notable exceptions, virtually every type of tectonic and sedimentary environment known to the science of geology is present in some province or area of the Greater Rocky Mountain Region. Although some aspects of certain areas, basins, and uplifts are similar, many of them are unique. Because this paper is an overview of the entire Region, only characteristic generalities will be presented and discussed.

## Generalized Geologic History

Major episodes of structural and sedimentary activity in the GRMR are shown in the series of maps and schematic cross sections contained in Figure 4.

In lower Paleozoic time, sedimentation was dominated by a large north-south trending miogeosynclinal basin that formed on a passive continental margin located in the western part of the GRMR (Figure 4a, map and cross section). Over 30,000 ft (9,200 m) of sediment were deposited in the geosyncline. Cambrian sediments are largely sandstones. Ordovician through Devonian rocks are largely carbonates. Throughout time, continental shelf edge and slope topography characterized the western margin of the geosyncline. In Devonian time, a sharp carbonate shelf edge was present in this area, and the western side of the Greater Rocky Mountain Region considered in this paper is defined by this shelf edge and adjacent basinal slope.

In Mississippian time, the western side of the GRMR was affected by the Antler Orogeny. (Figure 4b). The slope and deep-water oceanic facies (the "western facies") of the lower Paleozoic sedimentary section was thrust eastward over upper Paleozoic shelf carbonates by the Roberts Mountain ("Roberts") Thrust, and a large north-south trending foredeep basin was created. Many of the shales and silicic rocks of the overthrust western facies have high organic carbon content, and constitute oil-prone source rocks. Mississippian rocks derived from erosion of the Antler Geanticline were shed as a clastic section interfingering with deeper-water organic-rich shales of the Chainman Shale Formation in the foredeep basin to the east. A prominent carbonate shelf edge was present on the eastern margin of the foredeep, which contributed limestone turbidites moving from east to west into this general north-south trough. Mostly shallow water carbonates were deposited on the stable shelf further east. The Williston Basin was an area of subsidence and received a thicker section of sedimentary infill ending in an evaporite section overlain by upper Mississippian cyclic fluvial, estuarine and shallow marine sediments. Mid Pennsylvanian erosion or left the upper Mississippian section preserved in the Big Snowy Trough of central Montana.

Periodic base level changes controlled periods of non-deposition or erosion during lower and middle Paleozoic time. Regional pre-Pennsylvanian erosion, was responsible for the absence of rocks of these ages over much of the Lower to Middle Paleozoic Transcontinental Arch.

The Ancestral Rockies Orogeny produced a series of uplifts and basins in the central and southern GRMR during Permo-Pennsylvanian time (Figure 4c). Much of the lower Paleozoic section was removed over the uplifts, and clastic debris was deposited in adjacent areas. A cyclic section of marine to continental rocks was deposited in more distant areas. Black shales associated with these cycles represent a deepening or transgression and generally constitute rich oil-prone source rocks. A thick section of salt and cyclic interbedded black shales surrounded by "reefy" shelf carbonates was deposited in the Paradox Basin.

A major period of structural and sedimentary activity occurred in the Cretaceous Period (Figure 4d). Eastward thrusting associated with the Sevier Trust Belt created a large foredeep geosyncline that extended from the Gulf of Mexico, across the GRMR, into Canada and Alaska. There was igneous intrusive activity in the future eastern Great Basin area west of the Sevier Trust Belt. A thick section consisting predominantly of sandstones and shales was deposited in the Cretaceous Cordilleran Geosyncline (Figure 8 - to be discussed later). This section contains source rocks and reservoirs that are associated with much of the historic oil and

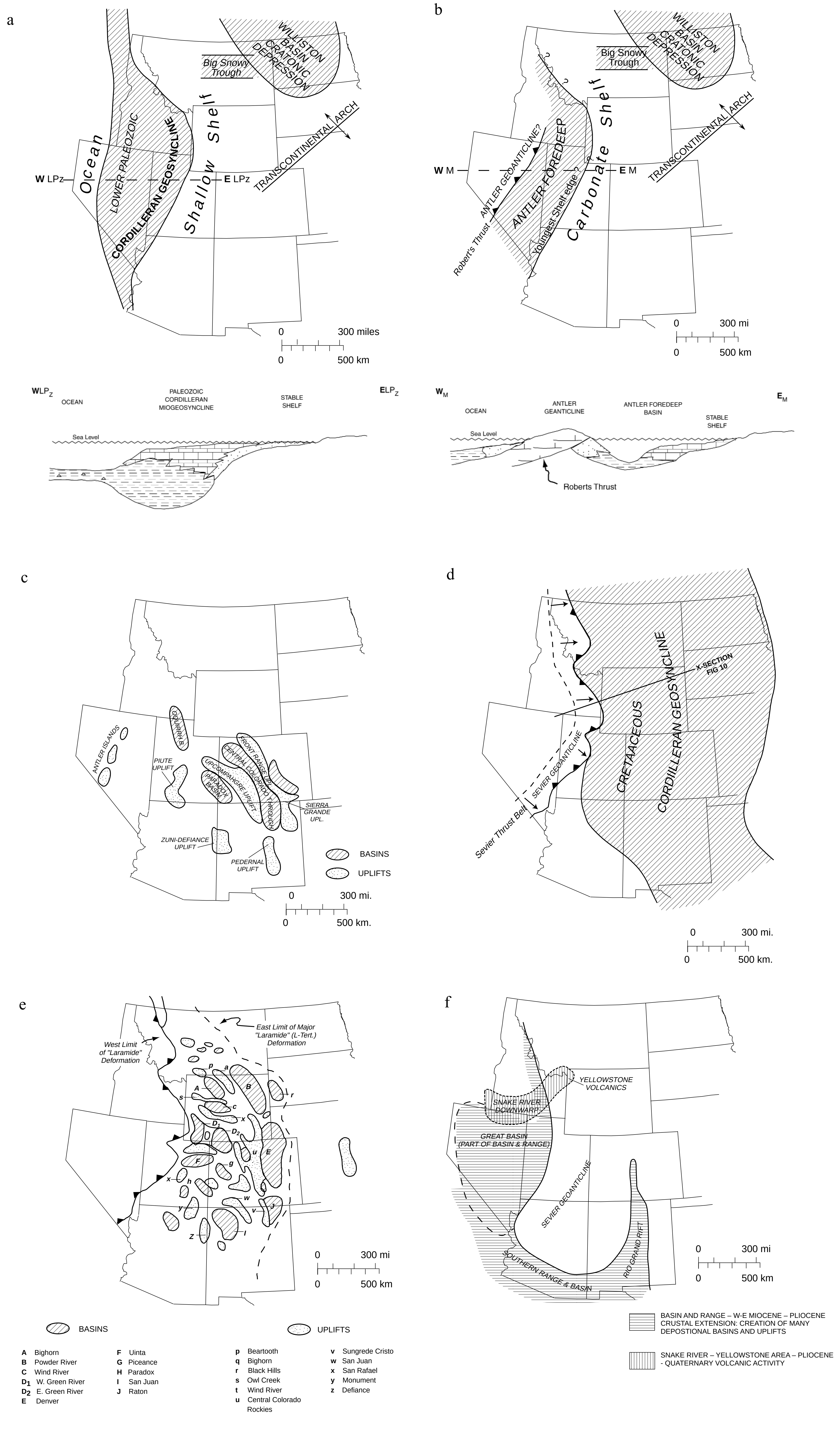



Figure 4. Generalized depositional and structural history of the Greater Rocky Mountain Region at key intervals of geologic time: a) Lower Paleozoic, b) Mississippian, c) Permian-Pennsylvanian, d) Cretaceous, e) Eocene-Paleocene, f) Quaternary and Pliocene-Miocene.

gas production in the GRMR. The Cretaceous Cordilleran Geosyncline probably contains most of the yet to be discovered hydrocarbons.

The Lower Tertiary Paleocene-Eocene Laramide Orogeny created most of the structural pattern characterizing the present-day central and northern GRMR (Figure 4e). Modern mountain ranges of the central Rocky Mountains were uplifted and much of the sedimentary cover was eroded, exposing crystalline igneous and metamorphic basement. The clastic material derived from the uplifts was deposited in adjacent basins. The thickness of early Tertiary rocks deposited in the basins is largely responsible for triggering hydrocarbon generation in older source rocks (See Figure 8). Oil-prone source rocks were deposited in lacustrine environments present in the Piceance, Uinta, Green River and Wind River Basins. Similar rocks were deposited in lakes present west of the Sevier Uplift in the eastern Great Basin. Gas-prone coal measures were deposited in the Wind and Powder River Basins. Scattered igneous intrusion occurred during this time period with associated hydro-thermal activity, especially in central Colorado.

Volcanic extrusive rocks were deposited in certain areas of the GRMR during the Oligocene (Figure 2). This event may have influenced source rock maturity in these areas; however, prospective sedimentary sections may be preserved in some rather large areas beneath volcanic cover.

During the Upper Tertiary, regional tectonic compression that controlled most of the structural development of the GRMR during the Cretaceous and Lower Tertiary was replaced by a period of extensional rifting which affected the western and southern parts of the area (Figure 4f). Listric normal faulting created a series of generally north-south trending uplifts and basins that characterize the present-day Basin and Range physiographic province in Nevada, southern Arizona and New Mexico. The Rio Grande Rift valley and adjacent basins of central New Mexico are related to this event. Highly variable thicknesses of material eroded from the mountain ranges were deposited in these rift basins. Extrusive igneous rocks were deposited in the Snake River Downwarp of southern Idaho (Figure 2) and a few other scattered places during the latest Tertiary and into the Quaternary. Prospective sections of sedimentary strata with abundant shows are present within this overall rift basin and there may be additional prospective sediments present beneath volcanic cover.

## Structure

The Greater Rocky Mountain Region contains a wide variety of structural settings which characterize both singular and specific groups of provinces and specific periods of time. Basin classifications fall in such categories as: 1) passive continental margin miogeosynclines (Lower Paleozoic of the eastern Great Basin), 2) subsiding cratonic depressions (Williston Basin), 3) foreland geosynclines (Antler and Cretaceous Cordilleran Geosynclines), 4) intermontane and peri-montane basins (Ancestral Rockies and Laramide Basins) and 5) extensional rift grabens and half-grabens (individual basins in the Basin and Range, Snake River Downwarp and Rio Grand Rift Provinces).

Structural styles represented in the various structural settings include: 1) compressive “thin-skin” thrusts and folds (Powers, 1982), 2) compressive high angle reverse faults involving basement associated with basin margins and force-fold features (Lowell, 1983; Stone, 1993), 3) extensional listric and high angle normal faults creating horst block uplifts and graben basins (Wernicke, 1981; Gans and Miller, 1983; Effimoff and Pinezich, 1986; Camilleri, 1992), and 4) lateral shear zones (Stone, 1969) that have created subsidiary folds and fractured reservoirs, and which have influenced reservoir compartmentalization (Sonnenberg and Weimer, 1993; Warner, 1997). Structural configurations have also been created by salt movement (Barrs and Stevenson, 1981; Nitkind, 1982) and solution (Parker, 1967; Swenson, 1967; Garner, 1997) and meteor impacts (Brenan and others, 1975; Bridges, 1987; Koberl and Anderson, 1996; Forsman and others, 1996; Kries and others, 1999; Stone, 1999).

Major periods of structural deformation occurred in the Mississippian (Antler Orogeny), Permo-Pennsylvanian (Ancestral Rockies), Cretaceous (Sevier Orogeny), Uppermost, Cretaceous/ Lower Tertiary (Laramide Orogeny), Mio-Pliocene (Basin and Range/Rio Grande Rift Orogeny). Significant features related to these episodes are shown in the series of illustrations depicted in Figures 4a-4e.

### Stratigraphy, Depositional Environments, and Rock types

The sedimentary section present in the Greater Rocky Mountain Region ranges from Precambrian to Holocene in age (Mallory, 1972). Not all geologic periods are represented in all areas, and time gaps are present within standard periods and epochs. Depositional environments represented in the stratigraphic record at various places include a) deep and shallow marine, b) lacustrine and c) terrestrial, Resulting sedimentary rocks include course and fine-grained clastics, dolomite and limestone carbonates, and salt and anhydrite evaporites.

Intrusive and extrusive igneous rocks are present in certain areas and are Jurassic, Cretaceous, Tertiary, and Quaternary in age. Most pre-Upper Tertiary rocks are acidic in composition, while those of Pliocene to Holocene in age are basaltic. Layered extrusive rocks are generally intercalated with sediments and serve as cover in some large areas, and provide reservoirs in certain oil fields of the Great Basin.

## PETROLEUM SYSTEMS

An understanding of petroleum systems and how they operate can be of benefit in assessing discovery potential in a region (Magoon and Dow, 1994, Smith 1994). At least thirty distinct petroleum systems defined by the distribution of source rocks and reservoirs exist on the Greater Rocky Mountain Region. The distribution of these critical lithologic elements demonstrates that some systems are unique to a given basin or province, and some are common to several. Identified source rocks have charged reservoirs in a variety of traps and accumulations through both lateral and vertical migration paths.

### Source Rocks and Reservoirs

The occurrence of source rocks and reservoirs in relation to geologic age and orogenic events that controlled major depositional sequences related to cratonic onlap, offlap or erosion is shown in Figure 5.

Known source rocks and productive reservoirs span the age interval from Pre-Cambrian through Tertiary. The spectrum of source rocks includes those that contain all of the basic kerogen types: oil-prone Type I, oil-prone Type II, and gas-prone Type III. The relationships of source rocks to the reservoirs they have charged is summarized in Table 2.

Hydrocarbon production has been established from a wide variety of reservoir rocks including a) sandstones, limestones and dolomites with matrix porosity and permeability, b) fractured dense carbonates, shales and igneous rocks and c) bedded coals. Considerable exploration opportunity appears to exist in ventures targeting nonconventional reservoirs in low-permeability “tight” rocks, fractured rocks, and coals.

### Tight gas reservoirs

Tight gas reservoirs found primarily in Cretaceous sandstones and chalks generally have permeabilities that are too low to permit economic production rates using conventional completion techniques. Their characteristics and occurrence have been the subject of considerable study in the past few years (Spencer, 1989; Spencer and Mast, 1986).

# RELATION OF DEPOSITIONAL SEQUENCES TO ROCKY MOUNTAIN OIL & GAS OCCURRENCE

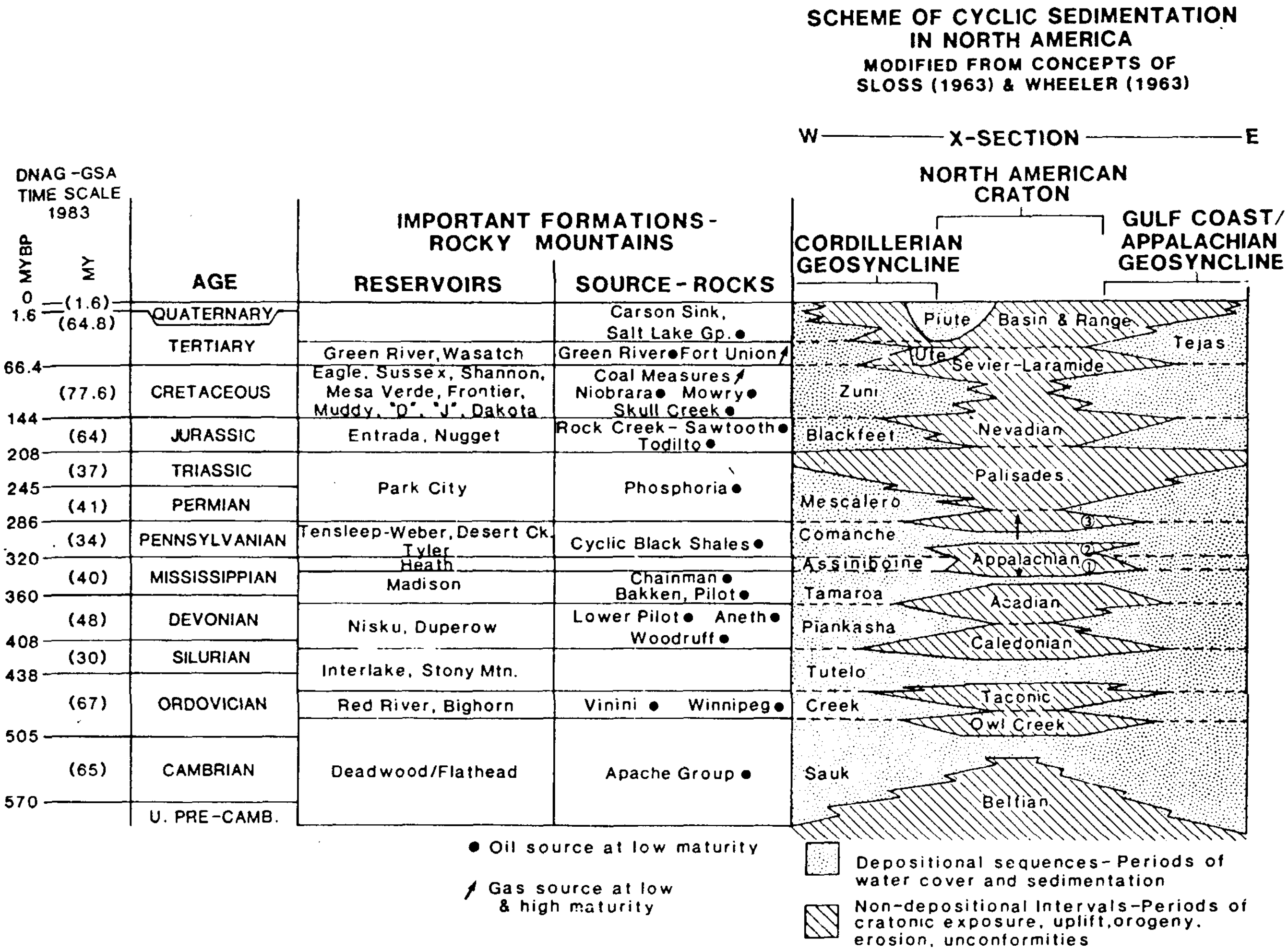



Figure 5. Stratigraphic chart showing ages and names of significant productive oil and gas reservoirs and source rocks together with their position in major depositional sequences (Meissner and others, 1984).

Chalks found in the Niobrara Formation are productive of biogenic gas in shallow low-relief structures on the east flank of the Denver Basin (Pollastro and Scholle, 1986). Porosities range from 50 to 25% and permeabilities range from 16 to 0.1 md with an average of about 1 md in the depth range of 1000-3200 ft (300-975 m). The first commercial wells drilled with air and completed open hole had initial potentials of 20-60 MCFG (850-1,700 cu. m) per day. Fracture stimulation techniques and low cost drilling and completion techniques have greatly enhanced the economics of production. Porosity and permeability decrease beyond reasonable productive reservoir limits at depths greater than about 4000 ft (1220 m). However, there appears to be a large prospective area extending along the east flank of the Denver Basin and into central South Dakota, where depths are sufficiently shallow.

TABLE 2
MAJOR PRODUCTIVE PETROLEUM SYSTEMS

| SOURCE ROCK | AGE | RESERVOIR ROCK | AGE | BASIN(S)/AREA(S) |
|---|---|---|---|---|
| Green River* (lake core facies) | Eocene-Paleocene | Wasatch-North Horn (lake margin, fluvial facies | Eocene-Paleocene | Uinta, W. Green River |
| Sheep Pass* (lake core facies) | Eocene | Fractured Sheep Pass & Tertiary volcanics; Ely Ls & Devonian-Siluria Dolo | Eocene, Oligocene, Pennsylvanian Devonian, Silurian | Railroad Valley in eastern Great Basin |
| Tongue Riv. Coal*** | Paleocene | Tongue River Coal*** | Paleocene | Powder River |
| Oil Prone**: Sharron Spgs Sh Niobrara Fm Mowry Sh Skull Creek Sh | lower-Upper and Lower Cretaceous | Fracured source rocks Ss in Mesaverde, Frontier, Gallup, Muddy, "D" and "J" Dakota, Lakota Fms | Upper and Lower Cretaceous | Sweetgrass Arch, Bighorn, Wind River, Powder River, Laramie Green River, Piceance, Uinta, N. Park, Denver San Juan |
| Gas Prone***: Coals in Fruitland, Raton, Vermejo, Mesaverde, Ferron Fms | Upper and Lower Cretaceous | Ss & coals in Fruitland, Pictured Cliffs, Raton, Vermejo, Mesaverde, Ferron Fms | Upper and Lower Cretaceous | Wasatch Plateau Green River, Uinta, San Juan, Raton |
| Phosphoria Fm** | Permian | Park City Fm carb. Tensleep & Weber Ss, M. & L. Paleozoic carb. and ss, Crystalline basement | Permian Pennsylvanian Mississipian, Ord.,Cambrian, PreCambrian | Bighorn , Wind River, Green River, Piceance |
| Cyclic Black Shs** | Permian, Pennsylvanian | Minnelusa & Leo Sds, Permian & Pennsylvanian Ls, Dolo & Ss | Permian, Pennsylvanian | Powder River, Denver |
| Cyclic Black Shs** | Pennsylvanian | Fractured Sh (Kane Cr.) Carbonate mounds | Pennsylvanian | Paradox |
| Cyclic Black Shs* in Tyler & Heath Fms | L. Penn.- U. Miss. | Ss in Tyler & Heath Fms Amsden Ls. | Pennsylvanian- U. Mississippian | Williston, Central Montana |
| Bakken & L. Miss. Shs** | Mississippian & uppermost Devonian | Fractured Bakken; Madison Gp Ls & Dolo Sanish Sd, Nisku carb. | Mississippian, U.. Devonian | Williston |
| Chainman Sh** | Mississippian | Tertiary volcanics, Devonian-Silurian Dolo | Oligocene, Dev.-Sil. | Railroad & Pine Valleys in eastern Great Basin |
| U. Red River Shs** | Ordovician | Interlake, Stony Mtn., Red River Ls & Dolo. | Silurian, Ordovician | Williston |

*Type I kerogen, **Type II kerogen, ***Type III kerogen

Matrix permeability and porosity in sandstones generally decrease with increasing depth of burial and approach values that would seem to indicate uneconomic production capability (Law and others, 1986; Schmoker, 1997). However, substantial gas production has been established from so-called “tight” sandstones which generally have permeabilities of 0.5 md or less. Sandstone lithologies in the Cretaceous and Lower Tertiary are highly variable (Coalson, 1989). Most are characteristically fine- to very-fined grained and consist dominantly of quartz; however, lithic fragments, feldspar grains and primary depositional clays may be large contributors to overall lithology. Grain size and grain composition depend on the lithology of the source area and on distance and transport mechanism to the site of deposition. Depositional facies are an important control on reservoir distribution. Although more-porous and -permeable sandstones may be developed in such facies as channels, point bars and overbank deposits, they are also related to marine shorelines and bars, where substantial winnowing of fine grains and clays has taken place. These facies are often associated with “sweet spots” in deep-basin gas accumulations Although primary depositional composition is highly important, all Rocky Mountain low-permeability sandstones have been subjected to extensive diagenesis (Byrnes, 1996).

Principal processes that have controlled Present day porosity and permeability include 1) grain rearrangement, 2) plastic and brittle deformation, 3) quartz pressure solution suturing, 4) quartz and calcite cementation, 5) dissolution of lithic rock and feldspar grains, and 6) precipitation of authigenic clays. These processes have resulted in the destruction of much of the original intergranular porosity and left dissolved grain porosity, clay-filled pores, and sheet-like connecting intergranular pore throats that are extremely susceptible to stress constriction. Irreducible water saturations may be unusually high. Studies of specific formations in certain basins have reached generally similar conclusions (Law and others, 1986; Pittman and others, 1986; Weimer and others, 1986).Even though permeability is low, porosities may range from 5-20% and provide ample storage capacity for gas. Many tight sandstones are naturally fractured, and this greatly increases the permeability. Modern methods of well stimulation by artificial hydraulic fracturing have allowed successful economic exploitation of these types of reservoirs. Tight sandstones constitute one of the most important reservoir targets for future exploration in the GRMR.

## Fractured reservoirs

Many, if not most, of the productive oil and gas reservoirs in the GRMR are fractured to some degree. Fracturing enhances the productive capability of reservoirs with effective matrix porosity and poor matrix permeability through the addition of fracture permeability. Many carbonate reservoirs in the GRMR could not be economically exploited without the presence of natural permeability-enhancing fractures. Natural fracturing is an essential characteristic in tight sandstone reservoirs found in a deep-basin setting (Pitman and Sprunt, 1986). Fracturing also creates reservoir porosity and permeability in rocks with negligible amounts of matrix porosity and permeability, such as dense carbonates, shales, and igneous rocks. Many reservoirs of this type in the GRMR are found in mature source rocks and represent an indigenous type of accumulation. Fracturing in source rocks and other low matrix permeability rocks within the deep-basin setting is believed to have been initiated by hydrocarbon generation producing overpressures (Meissner, 1974; Bredehoeft and others, 1994). We believe fractured reservoirs in source rocks and tight gas sands in the deep-basin settings of several Rocky Mountain basins are a significant exploration target for the discovery of future reserves.

## Coalbed Methane (CBM) reservoirs

Bedded Cretaceous and Lower Tertiary coals provide one of the major future exploration and exploitation targets in the GRMR. They serve as both sources of indigenous gas found within the coals as well as sources of expelled gas that charge other reservoir types (Rightmire and Choate, 1986). Coals have peculiar and unorthodox reservoir properties when compared to reservoirs with conventional matrix porosity and permeability. An understanding of these properties and characteristics should aid in predicting likely places for exploration.

Basic principles of thermal gas generation and storage according to the model proposed by Juntgen and Karweil (1966), are shown in the graphs of Figure 6.

Thermal generation of methane from coals is reflected through the loss of volatile matter (VM). This is shown by increasing coal rank and by increasing vitrinite reflectance (Ro). As shown by the generation curve (A) in Figure 6a, thermal methane generation begins in a high-volatile bituminous A coal at 37.8% VM, equivalent to an Ro of 0.73% and will generate up to 9019 cu. ft/T (282 cc/gm) upon reaching an anthracite rank characterized by 5% VM and Ro 3.5.

Not all of the methane thermally generated from coal is released or expelled for migration to a conventional matrix or fracture reservoir. Coals have a significant capacity to retain, store or “adsorb” methane, and this capacity may exceed generation volumes at low coal ranks. Low rank coals will adsorb gas if it is available to

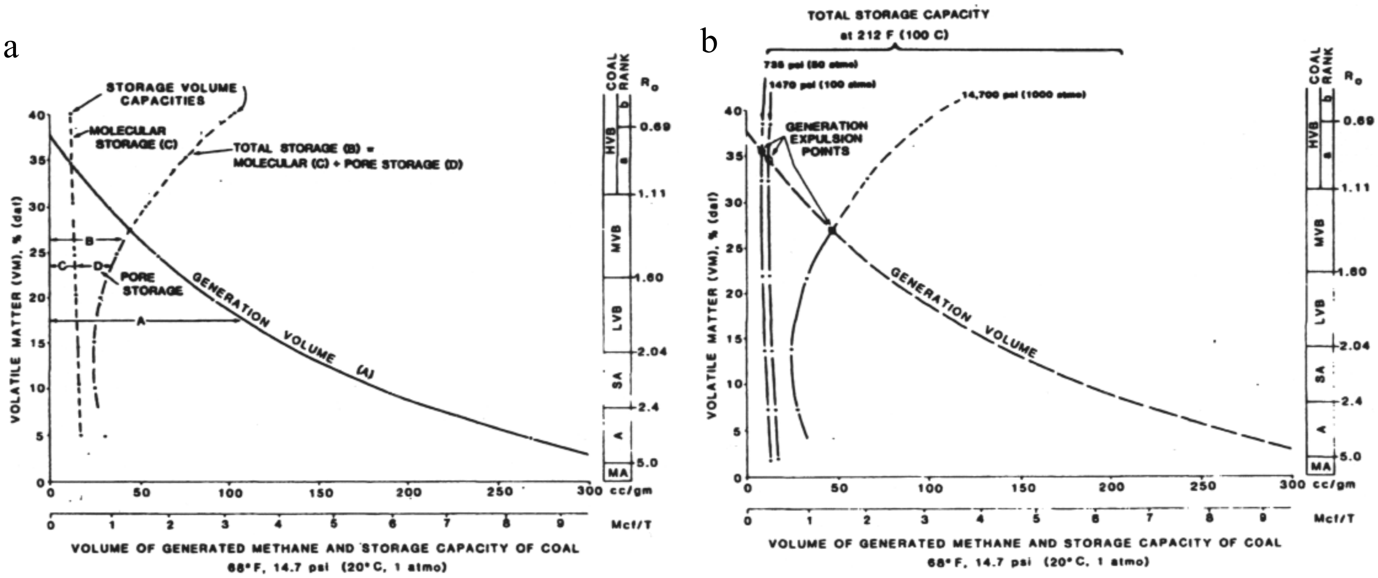



Figure 6. Generation and storage of gas in coals as a function of coal rank: a) Theoretical generation with and sorption and pore storage volumes at 14.7 psia and 68˚F (1 atmo., 20˚C); b) Theoretical generation and storage volumes at variable pressures and constant 68˚F (20˚C) (Meissner, 1984).

them. Storage is accomplished by two processes: 1) “adsorption” within or upon the molecular structure of the coal kerogen, and 2) conventional volume storage within micropores present in the coal. The volume of methane stored by the sum of these two processes is dependent upon coal rank, temperature and pressure. Figure 6a shows storage volumes for each of these processes and their sum at 68˚ F and 14.7 psi (20˚ C, 1 atmo.). Molecular storage is shown to increase slightly with increasing rank and to be of more significance than pore storage at higher ranks. Pore storage is indicated to be of more importance at lower ranks, and, although the graph does not show storage for ranks lower than high volatile B bituminous coals, it is inferred that sub-bituminous and lignite ranks might have relative large pore storage capacities.

Total storage capacities decrease with increasing temperature but increase with increasing pressure. The effects of pressure on storage are shown in Fig 6b. Expulsion is shown to be possible when generation volume exceeds pressure-dependant storage capacity. If a coal is gas-saturated at high reservoir pressure, and the pressure is lowered, storage capacity becomes less and gas is released for expulsion-migration. This is a primary mechanism for the production of coalbed methane through wells that lower the pressure surrounding the wellbore.

The gas generation and storage curves presented in Figure 6 are somewhat generic, and actual quantitative values depend on actual coal types and compositions, as well as the thermal generation model assumed. In addition to thermally generated gas, which is characterized by high concentrations of the heavy carbon isotope $^{13}C$, many coalbeds have been found to contain variable proportions of methane enriched in the “light” carbon isotope $^{12}C$, which is generally believed to be of biogenic origin (Rice, 1993; Scott, 1993). Biogenic gases found in coal are thought to have been generated by methane-generating bacteria that were introduced from the surface by dynamic groundwater and which have subsequently used the coal as an energy source (Scott and others, 1991). Biogenic gases may charge low rank coals that have not thermally generated methane. They may also mix with or dilute thermal methane.

Most shallow coal beds have developed a “cleat” or extensional fracture system (Close, 1993). Production of gas from a coal involves molecular diffusion from the coal matrix into the fracture system, followed by Darcy-type movement through the fracture system into a wellbore. Coalbed methane production is generally characterized by modest rates and long life. An unusual feature of reservoir behavior is the fact that production rate characteristically increases with time before decline begins. Even though the coal matrix may be more-or-less saturated with gas, the fracture system in most shallow coals is filled with groundwater, and these must be “dewatered” before maximum production potential is achieved  The dewatering process generally involves handling and disposing of large volumes of water and this effects economics and may have an environmental impact.  The cleat system found in shallow coals provides a critical element of permeability that controls economic rates of production.  The effectiveness of the cleat system appears to diminish and disappear at depths of 4000-5000 ft (1220-1525 m).  Even though more-deeply buried coals may contain large volumes of gas, their exploitation is currently limited by the absence of an effective cleat system. Developing a technology to exploit this resource will create a significant exploration and development opportunity.

## Types of Traps and Accumulations

Oil and gas production in the GRMR has been obtained from virtually every type of “trap” and “accumulation” setting known to the science of petroleum geology, and includes a wide variety of ”classical”, “traditional”, or “conventional” types as well as those considered “unorthodox” or “unconventional”. Figure 7 contains a simple diagrammatic sketch that depicts the general setting of trap types and classifications as used by  the USGS (1995) and subsequently modified by Surdam (1997a) and the authors of this paper. The diagram is particularly descriptive of oil and gas accumulations in the Rocky Mountain Region.

### “Conventional traps”

In Figure 7, conventional traps (called “discrete-type” accumulations by the USGS) are depicted in a typical setting on the shallower flanks of the basin.  Although not shown, combination-type traps consisting of both structural and stratigraphic elements also belong to this realm.  Structural traps include simple anticlinal closures related to such processes as thrusting, draping, salt movement or solution.  Stratigraphic traps include those related to subcrops, lateral facies changes and erosional topography. Hydrocarbon accumulations in most of these settings are underlain by water, which regionally saturates the reservoir.  The oil and gas saturating these accumulations is in a static state and they are, therefore, “trapped”.  Although the hydrocarbon phase saturating these accumulations is in a static or “trapped” state, the groundwater surrounding or underlying it is generally in a dynamic state and this situation often has great affects in controlling accumulations.  For instance, oilfields with tilted oil-water contacts on “unclosed” structural noses have been found.

### “Unconventional accumulations”

The GRMR contains a number of significant “unconventional” types of accumulations. Examples include those associated with gas production from coal beds, and those associated with “deep-basin”, “basin center”, or “continuous-type” accumulations.  These last three names are used somewhat interchangeably; however, not all “continuous-type” accumulations are related to the same processes that cause deep-basin or basin center accumulations. The USGS has used the term “continuous-type” to cover all accumulations of a more-regional nature, with no clear evidence of a controlling classical trap style. Lignite coals containing biogenic methane and shallow accumulations of biogenic gas in shallow Cretaceous sands and chalks that are present in central and eastern Montana, in central South Dakota and eastern Colorado are clearly not the same type of accumulation as those commonly associated with the terms “deep basin” or “basin center”. All of these unconventional types of accumulations are of particular interest, as they have major exploration potential in the Rocky Mountain Region. They can also serve as “type locality” analog examples for the rest of the world.

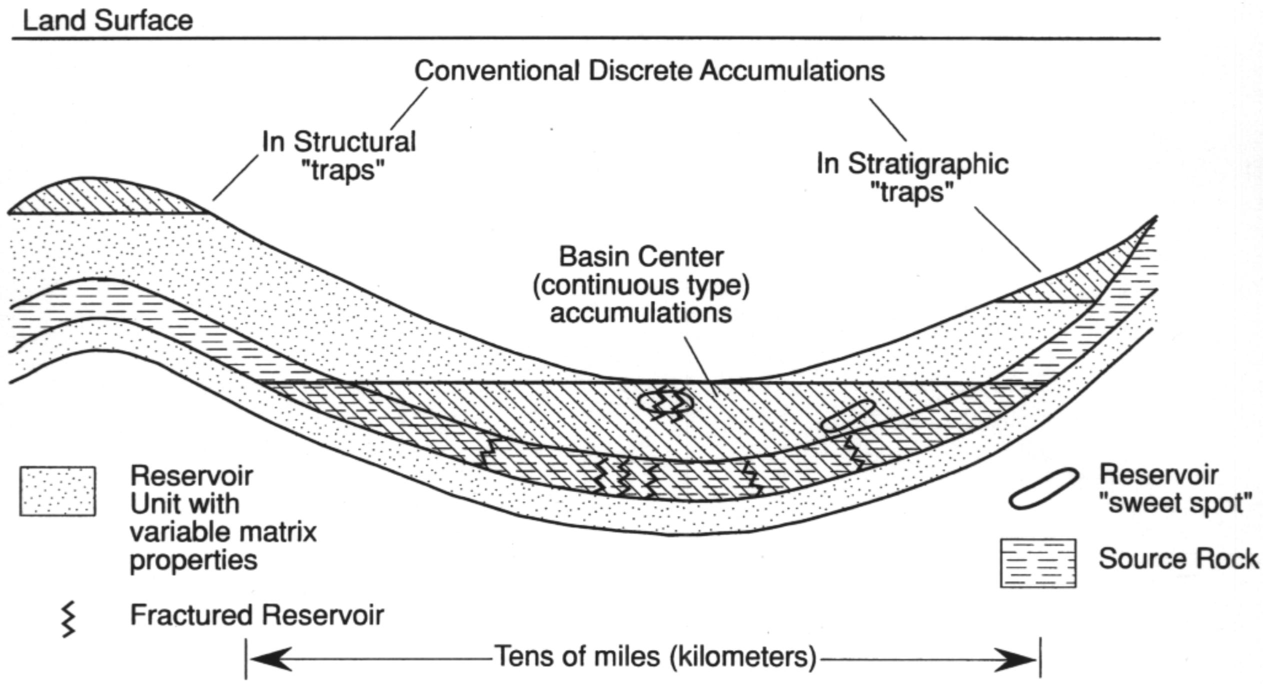



Figure 7. Simple classification of oil and gas accumulations found in the Greater Rocky Mountain Region (modified from Figure 5, U.S.G.S. Circular 1118, 1995 and Surdham, 1997).

A basin center accumulation is shown in the bottom of the syncline depicted in the cross section of Figure 7. This type of deposit is characterized by hydrocarbon-saturated reservoirs that are either significantly overpressured or underpressured with respect to normal. The accumulations are within or adjacent to mature source rocks that are either actively generating at high rates or that have ceased such generation in the relatively recent geologic past. Fractured reservoirs may be present within the source rock. Outward migration from the source rock may have also charged reservoirs with matrix properties; however, because of great burial depths, the matrix reservoirs are generally characterized by low porosities and permeabilities. Poor matrix permeabilities are commonly enhanced by fracturing. The accumulations have no basal hydrocarbon-water contacts, but are characterized by updip regional water saturations within reservoirs found in the same general stratigraphic interval. The species of hydrocarbons present (oil or gas) is controlled by both the stage of maturity achieved by the source rocks and the types of kerogen present in them.

The ubiquitous nature of reservoir saturation associated with mature source rocks indicates an area of supercharge and high migrational impedance. Conventional “trapped” accumulations are generally found along updip migration paths, suggesting that deep-basin accumulations leak excess hydrocarbon charge. Traditional concepts of petroleum geology consider that hydrocarbon entrapment is controlled by a “seal” at which migration stops or is retained by capillary seal capacity, and many investigators have attempted to explain the updip limit of deep basin hydrocarbon accumulations by various types of seals. Although updip limits of deep-basin accumulations may be controlled by capillary-entry or fracture-opening pressure, they may also reflect dynamic “back-up” in a region where generation rate exceeds that of migration. The volume of hydrocarbon saturation may not actually be “trapped”: it has “accumulated” and may dissipate with time.

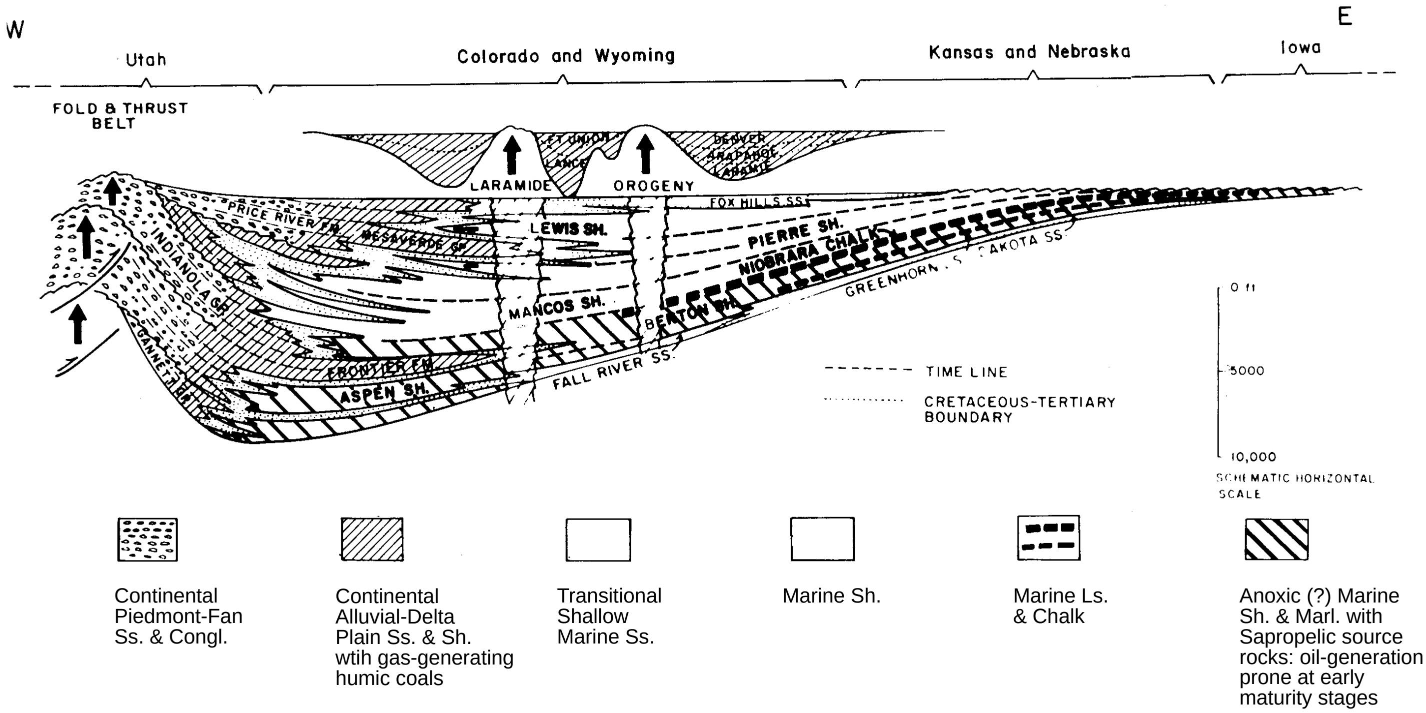



Figure 8. Schematic cross section through the Cretaceous Geosyncline showing the distribution of lithofacies, depositional environments and oil/gas source rocks. Also shown is the distribution of Tertiary rocks superimposed on the Cretaceous as a result of Laramide structural movement (after Kauffman, 1977 *in* Meissner and others, 1984).

Basin center accumulations generally involve large rock volumes and contain extremely large volumes of hydrocarbons; however, because of generally low reservoir porosity and permeability, most of these accumulations may be characterized by non- or sub-commercial production at the present state of exploitation technology. Local accumulations characterized by enhanced reservoir properties occasionally are present within a regional basin centered setting, and these constitute what are termed "sweet spots" where commercial production may be established. Sweet spots may be localized in areas of enhanced fracture or matrix permeability and porosity, either within the source rock unit associated with the accumulation or within a more-regional low quality reservoir that was charged by the source rock.

## CRETACEOUS PETROLEUM SYSTEMS

Petroleum systems present in the Cretaceous section of the GRMR have been some of the most important to historic production and probably constitute the major contributor to future development and discovery. The distribution of both oil- and gas-prone source rocks and the reservoirs they may charge within the syntectonic depositional sequence that filled the Cretaceous Cordilleran Geosyncline (Figure 4d) is shown in the schematic cross section contained in Figure 8.

Oil-prone source rocks containing Type II kerogen are present in minor cycles of transgression or basin deepening within the marine lower part of the section. Gas-prone source rocks are associated with humic coal

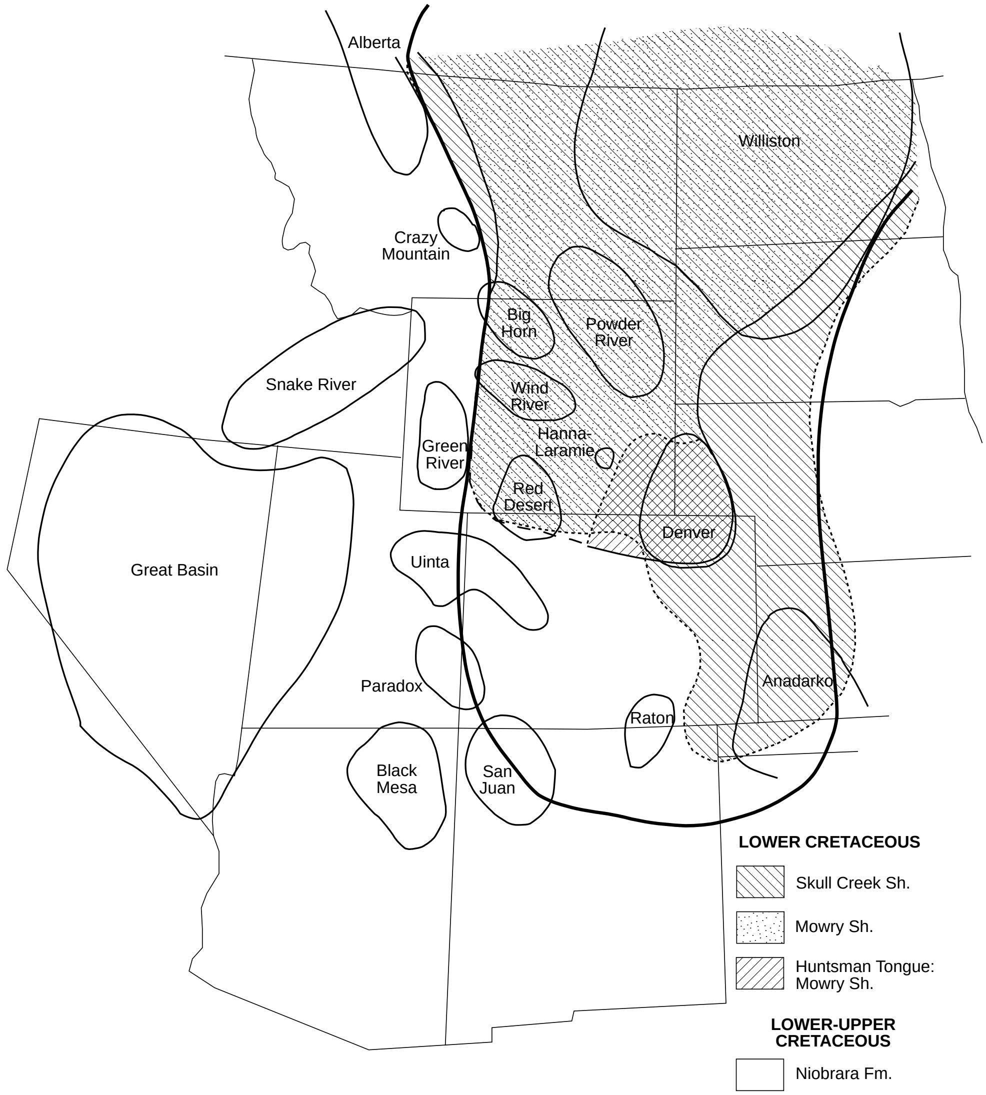



Figure 9. Distribution of Cretaceous-age oil-prone source rocks in the Greater Rocky Mountain Region. These rocks generate oil at lower stages of maturity and gas at higher stages. (Meissner and others, 1984)

measures containing Type III kerogen that are present within regressive cycles of terrestrial sedimentation that originate from the uplifted thrust belt on the west side of the geosyncline. Sandstone reservoirs are associated mostly with marine coastal interdeltaic, delta complexes and non-marine fluvial.

In early Tertiary time, the Cretaceous section was structurally deformed by the Laramide Orogeny. These sediments were eroded from mountain uplifts or buried to varying depths by lower Tertiary sediments derived from adjacent uplifts (Figure 8). Most of the maturity pattern present in Cretaceous source rocks was the result of Tertiary burial in the deepest part of the Laramide basins. Maturity in the lower part of the section along the western margin of the geosyncline was produced by burial beneath thrust plates or as a consequence of the thick Upper Cretaceous section.

Figure 9 shows the distribution of oil-prone source rocks in the lower part of the Cretaceous.

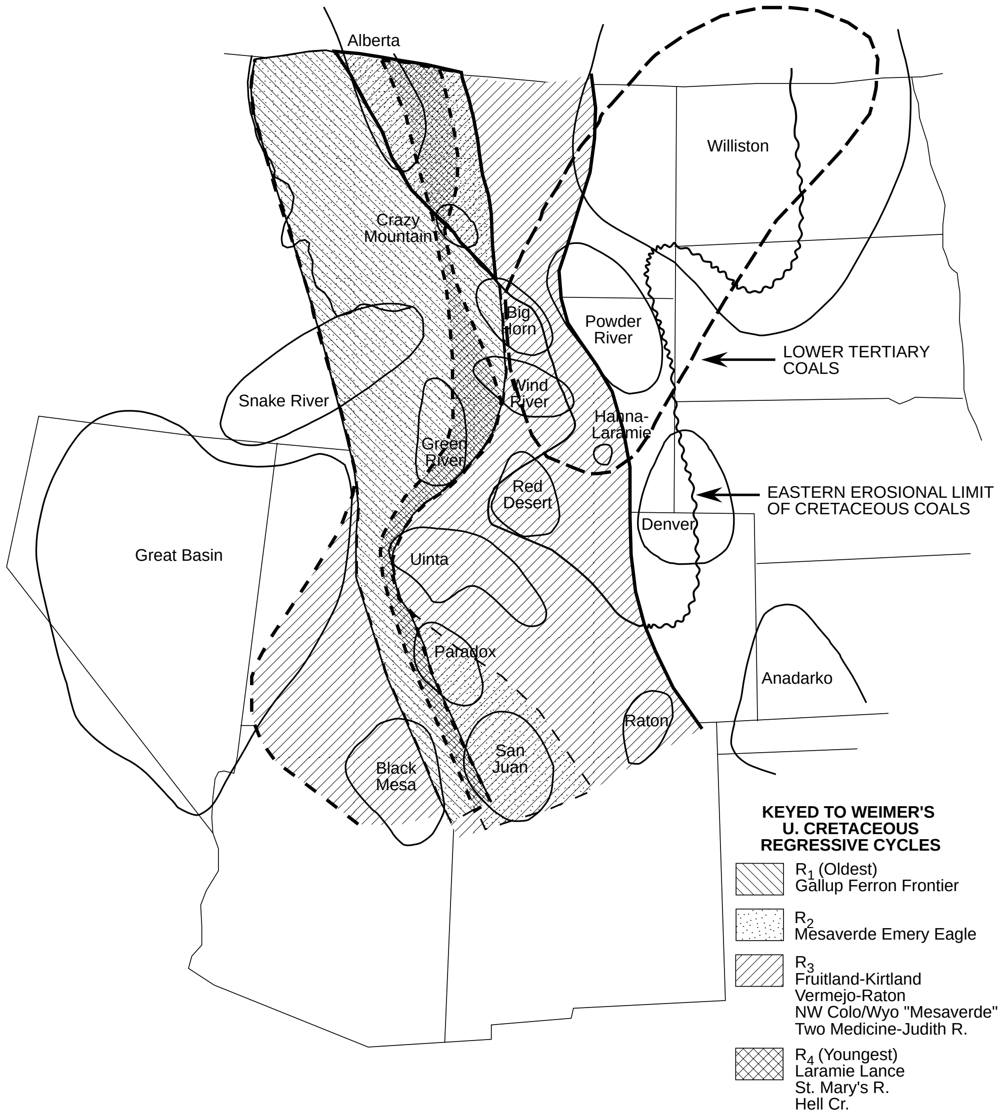



Figure 10. Distribution of Cretaceous and Lower Tertiary gas-generating coal measures in the Greater Rocky Mountain Region. Cretaceous units are keys to Weimer's (1960) regressive cycles. (Meissner and others, 1984)

These rocks are responsible for most of the oil found in Cretaceous sandstone, fractured source rock shale and limestone reservoirs. Although these rocks are basically oil-prone, where they have been more deeply buried in the centers of some of the Rocky Mountain basins or exposed to unusually high temperatures, they have generated gas. Oil in deeply buried or anomalously heated nearby reservoirs they have charged has also been converted into gas.

The depositional distribution of gas-prone humic coal measures in the Cretaceous and lowermost Tertiary is shown in Figure 10. Each individual coal measure in the Cretaceous is keyed to one of the regressive cycles recognized by Weimer (1960). The thickness and extent of these coals constitute a major global concentration of source rocks for the generation of world-class gas accumulations.

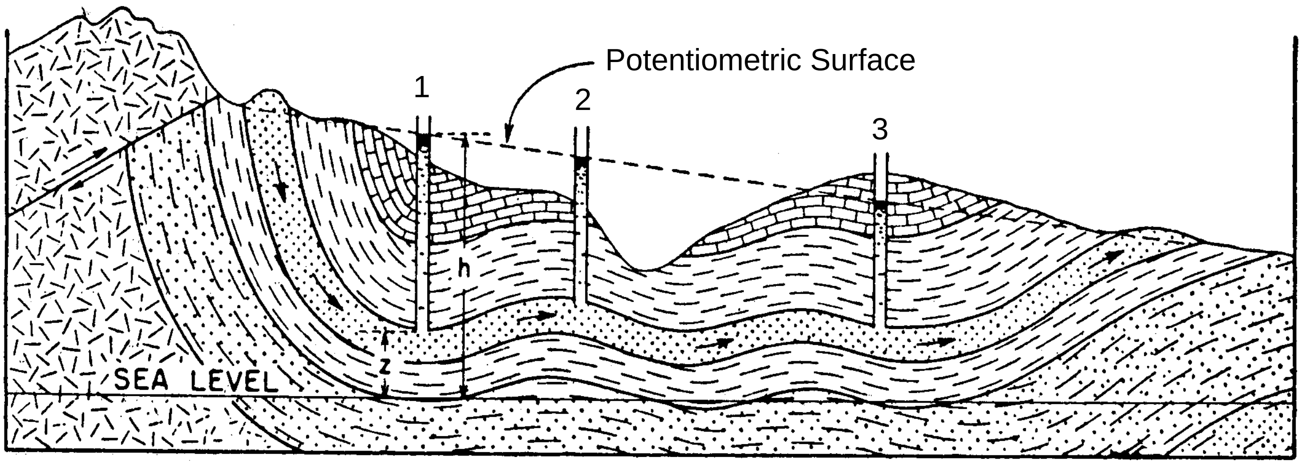



Figure 11. Cross section depicting regional flow of groundwater through an aquifer-reservoir from higher to lower outcrop elevation and a related potentiometric surface (from Hubbert, 1953). Because groundwater is capable of rising to the height (h) of the potentiometric surface in any well drilled into the reservoir, the relation of the potentiometric surface to ground elevation indicates that wells a and b will be overpressured in the reservoir, while well c will be underpressured.

## SIGNIFICANCE OF FLUID PRESSURE REGIMES AND HYDRODYNAMICS

Abnormally low "underpressure" and high "overpressure" are characteristic of many areas of the GRMR (Figure 17). Anomalous pressures in the Region are caused by two basic processes: 1) topographically driven groundwater flow (pervasive groundwater phase in the reservoir/ aquifer) and 2) hydrocarbon generation & migration (pervasive hydrocarbon phase in reservoir).

### Groundwater Dominated Fluid Systems

Because of the variation in outcrop topography between mountain uplifts and low-lying basins and sufficient amounts of precipitation and surface water flow, most subsurface reservoir sections in the GRMR are hydrodynamically active (Figure 11). This activity is commonly demonstrated by the presence of potentiometric gradients that are inclined toward the direction of groundwater flow. Active groundwater movement has influenced migration paths from source rocks to sites of accumulation and has caused commonly-observed tilted oil-water contacts (Hubbert, 1953; Dahlberg, 1982). The attitude of these contacts has affected the distribution of hydrocarbon accumulations on "closed" and "unclosed" structures (Murray, 1959; Vincillet and Chittum, 1981; DiMis, 1987; Berg and others 1994) as well as in stratigraphically controlled traps (Moore, 1984; Meissner, 1988). It has also greatly influenced the critical seal capacity of traps, with groundwater flow from the reservoir toward the seal reducing normal seal capacity. Conversely, flow from the seal toward the reservoir enlarges seal capacity (Stone and Hoeger, 1973; Berg, 1975; Schowalter,1976; Larber, 1981; Linn, 1981). Groundwater flow has also been shown to alter the subsurface thermal regime (Willet and Chapman, 1997) and to control coalbed methane saturation and composition (Oldaker, 1991, Scott and others, 1996)

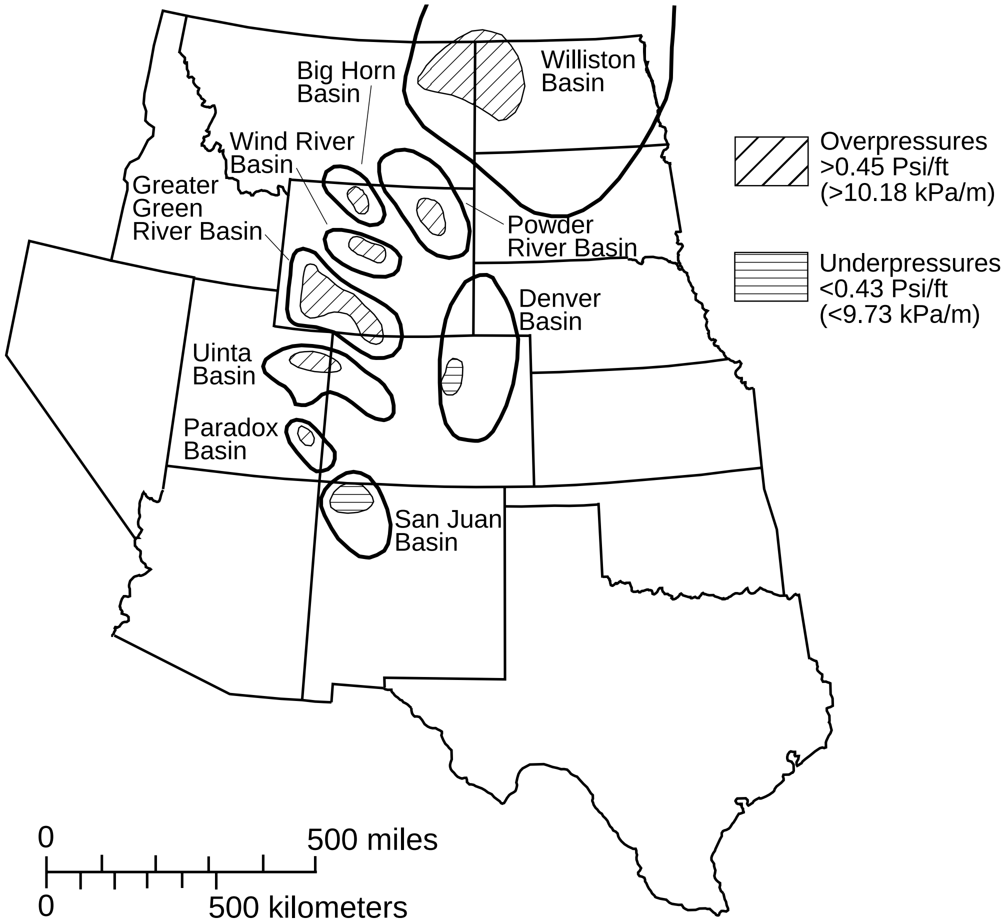



Figure 12. Map showing basins in the Greater Rocky Mountain Region with anomalous reservoir pressures associated with deep basin type oil or gas accumulations.

## Hydrocarbon Dominated Fluid Systems

Anomalous areas of both over- and under-pressure that are characterized by the presence of a predominantly hydrocarbon-saturated reservoir fluid system have been found in the deeper parts of several basins (Figure 12). These pressure anomalies form “cells” around a “core” of mature source rocks. Overpressures in this setting are believed to have been created during active hydrocarbon generation by volume changes produced during the conversion of immature solid kerogen into potentially expellable fluid hydrocarbons and kerogen residue (Meissner, 1974, 1980; Momper, 1980; Law, 1984; Law and Dickinson, 1985; Spencer, 1987; Bredehoeft and others, 1994).

The map shown in Figure 13 depicts a typical example of overpressure in the Cretaceous Mesaverde Group of the eastern Green River Basin of southwestern Wyoming. Pressures here are related to active gas generation in the bottom of the basin from coals contained in the Mesaverde (McPeek, 1981: Meissner, 1987). The area of source-rock maturity for the actively-generating coals corresponds to the area of overpressures where pore-fluid pressure gradients exceed 0.45 psi/ft (10.2 kPa/m). Although Mesaverde sandstones in the area of overpressure are pervasively gas saturated, commercial production has only been obtained in “sweet spots” associated with cleaner sandstones in marine shoreface or bar facies at the top of the Mesaverde.

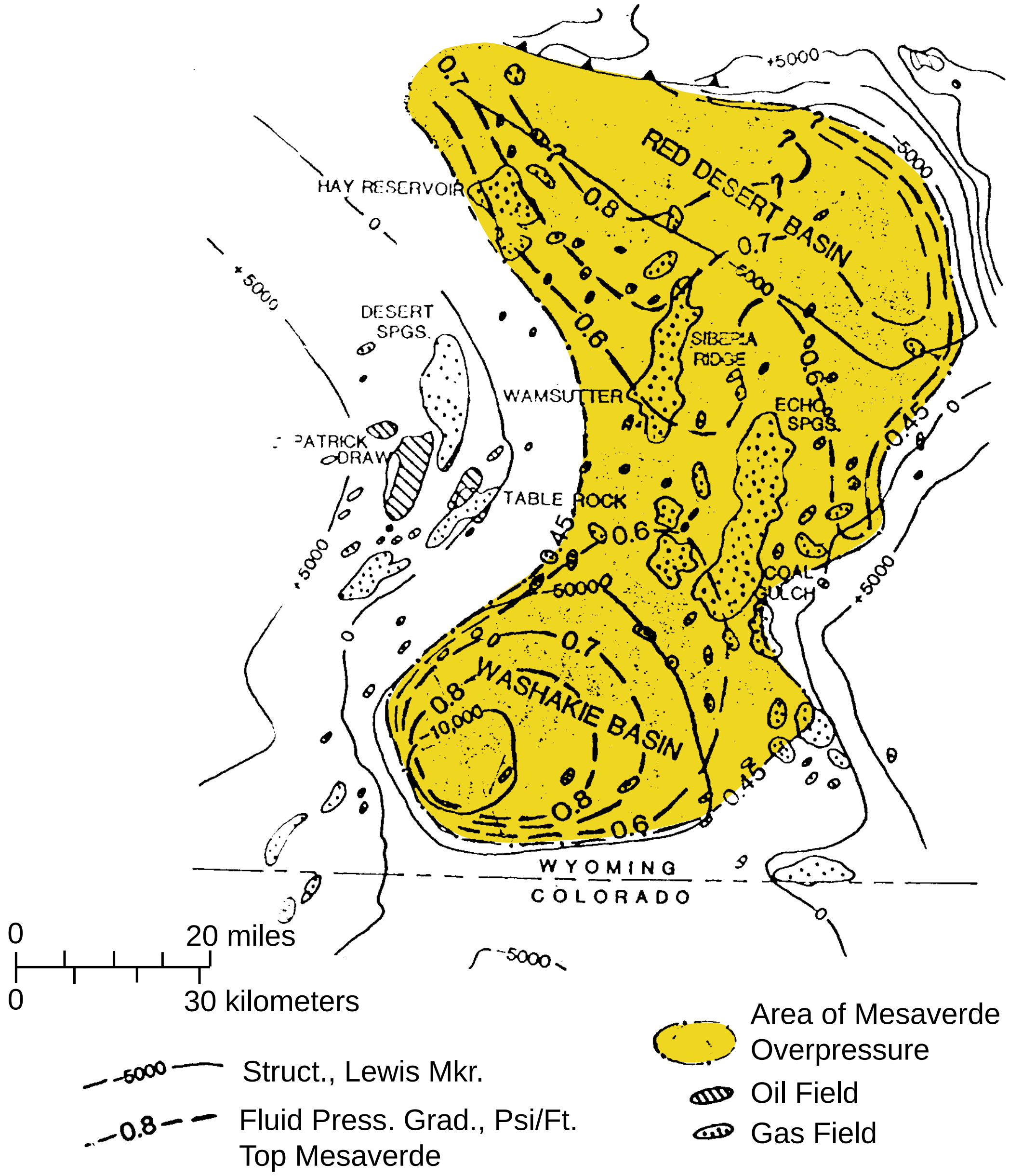



Figure 13. Map showing structure, the distribution of anomalous overpressures, and gas production in the Mesaverde (Cretaceous) section of the eastern Green River Basin (after McPeek, 1981).

The amount of overpressure created by hydrocarbon generation is governed by Darcy's Law and depends mostly on generation/expulsion rates, effective permeabilities, capillary and fracture barrier or seal capacities. Pressure may be transferred from the source rock to a reservoir along the expulsion/migration path. (Martinsen, 1997) Although hydrocarbon-phase overpressures may be maintained by stratigraphically or diagenetically controlled "capillary seals", the presence of generation overpressure is most-likely transient. In the transient case, the pervasive presence of hydrocarbons within a generation/expulsion cell is produced by a dynamic migration bottleneck, rather than by the presence of a classical static hydrocarbon "trap". Hydrocarbon generation is simply overwhelming the migration "pipeline" (Law and others, 1986).

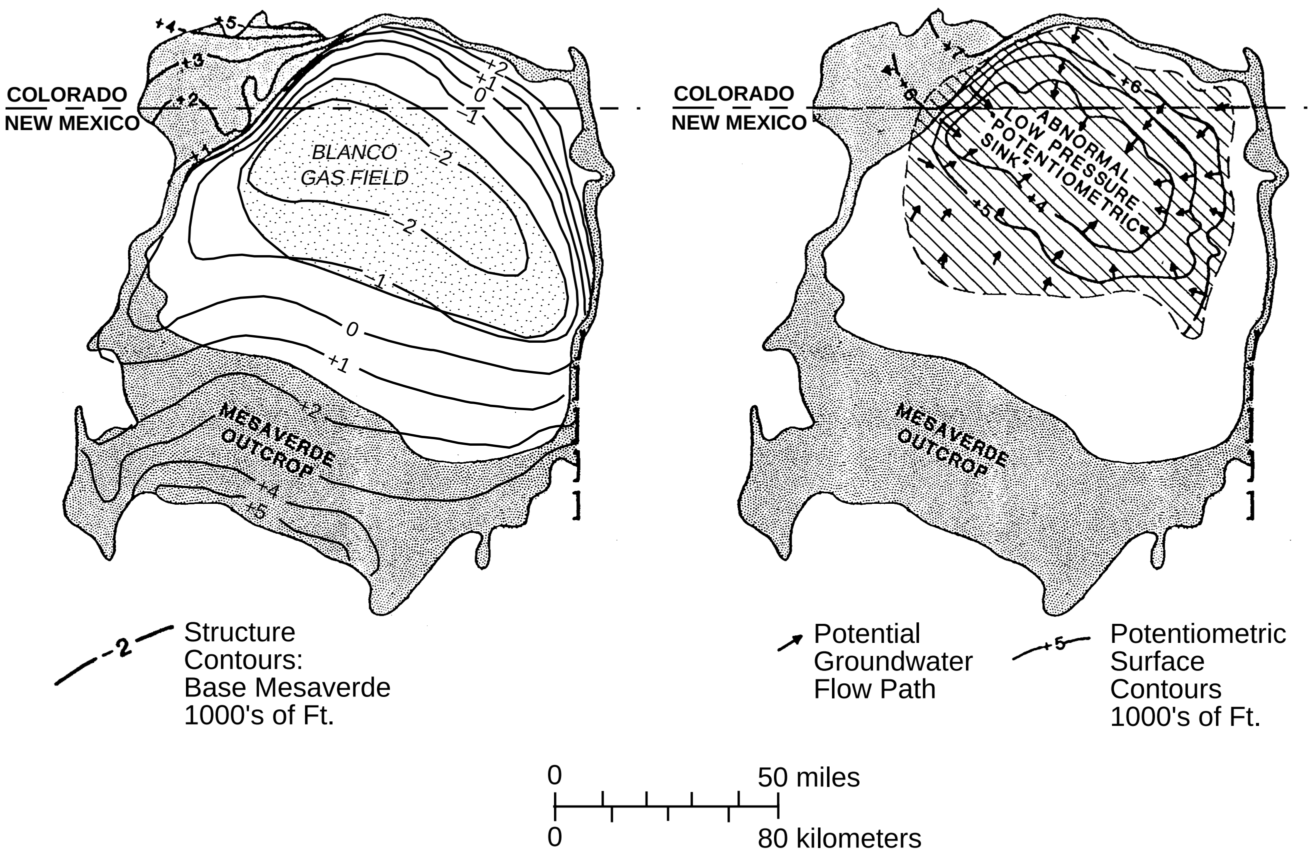



Figure 14. Maps depicting the distribution of anomalous underpressures and gas production in the Mesaverde (Cretaceous) section of the San Juan Basin (after Berry, 1959). a) Structure at the base of the Mesaverde and gas production. b) Potentiometric surface map of the Mesaverde showing the area of an anomalous underpressured “potentiometric sink” and potential flow paths for groundwater.

Underpressures associated with areas of pervasive deep-basin gas saturation may theoretically be caused by a number of mechanisms, including a) gas volume contraction produced by temperature reduction related to changing heat flow or uplift, b) gas readsorption from adjacent matrix reservoirs into coals when the temperature is lowered (Meissner, 1987), c) elastic porosity dilation produced during uplift and erosion (Bachu and Undershultz, 1995), and d) readjustment of pressure when the gradient of a gas column is re-equilibrated to shallower conditions produced during uplift (Surdam, 1997b). Underpressures may also be created in both deep-basin oil and gas accumulations by the transient migration process. When active high-rate generation ceases, overpressure created by the process will diminish if the hydrocarbons are able to leak off and migrate away from their deep basin position. As leak-off occurs, formation water will be imbibed into formation porosity, and this leads to conditions of under-pressure in the region formerly characterized by overpressure. Leak-off may be accomplished by conventional phase migration or by diffusion. Diffusion may be particularly important in the case of gas (Krooss and others, 1992, Nelson and Simmons, 1992, 1995). If pressures and migration are time-transient, under-pressures will remain until all mechanically unstable hydrocarbons have left the synclinal deep-basin position or are stabilized in conventional traps When this occurs the dynamic pressure regime will return to normal (Meissner, 1985).

An example of underpressures related to pervasive deep-basin gas accumulation is found in the San Juan Basin of southwestern Colorado and northeastern New Mexico (Figure 14). Deep-basin gas accumulation here is associated with the area of thermal generation in coals of the Mesaverde Group, as is the case for overpressured gas accumulation in the Green River Basin. Maturation models (Bond, 1984; Meissner, 1987;

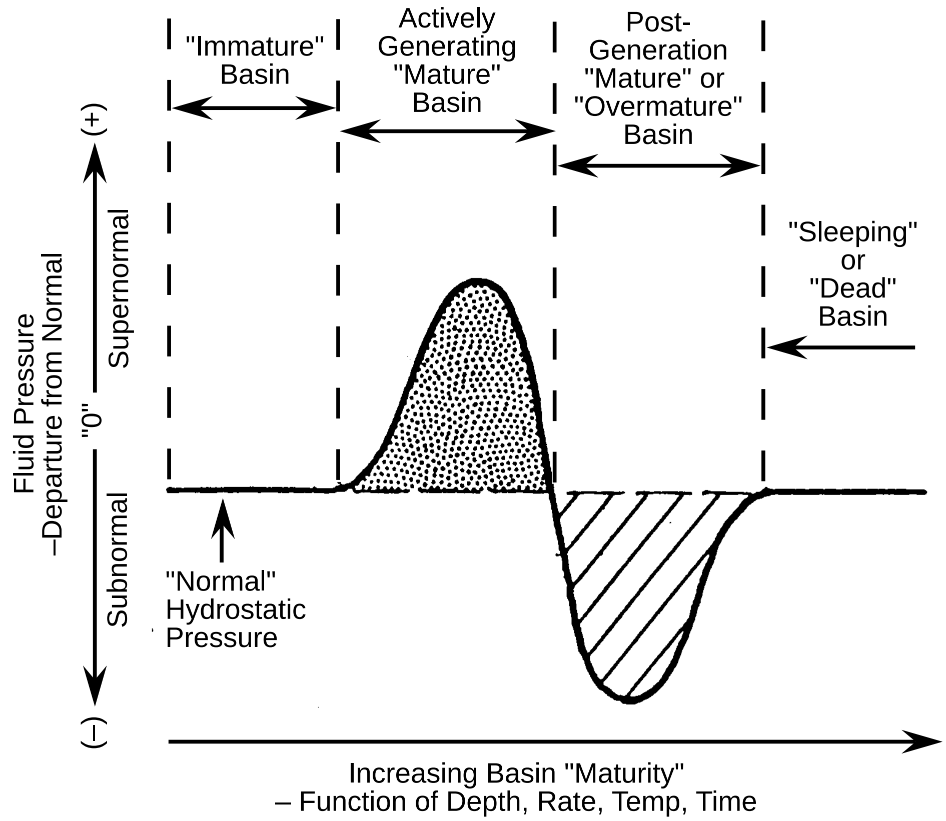



Figure 15. Evolution of fluid pressures in relation to hydrocarbon generation and migration in the setting of a deep basin accumulation (Meissner, 1987).

Law, 1992) indicate that maturity was achieved in the coals as a result of an abnormal Oligocene heating event related to igneous activity in surrounding areas. Gas generation began about 35 million years ago and ended about 15 million years ago. As is the present situation in the actively-generating Green River Basin, a large gas-saturated overpressure cell was undoubtedly present in the San Juan Basin at this time. A present-day potentiometric surface map for the Mesaverde is shown in Figure 14b. Potentiometric contours, which indicate elevations to which groundwater should rise based on the pressures measured in the reservoir, are substantially below ground surface elevation and demonstrate the presence of underpressure. Closed contours in the deep part of the basin are of minimum value and represent the existence of a “potentiometric sink” toward which groundwater is flowing. Although several processes may be contributing to this phenomenon, we believe the main mechanism creating the underpressured potentiometric sink is the loss of gas from the deep-basin gas accumulation by diffusion and the replacement of pore volume by water imbibition from the updip area.

The sequence of events described above for the time-transient behavior of anomalous pressures related to hydrocarbon generation represents a cycle of anomalous pressure buildup and decay (Figure 15). As long as the pressure cycle related to this phenomenon is in a state of either over- or underpressure, or in the geologically short time between these states when pressure is normal, economically viable accumulations of the “deep-basin type” may exist in the anomalous pressure cell.

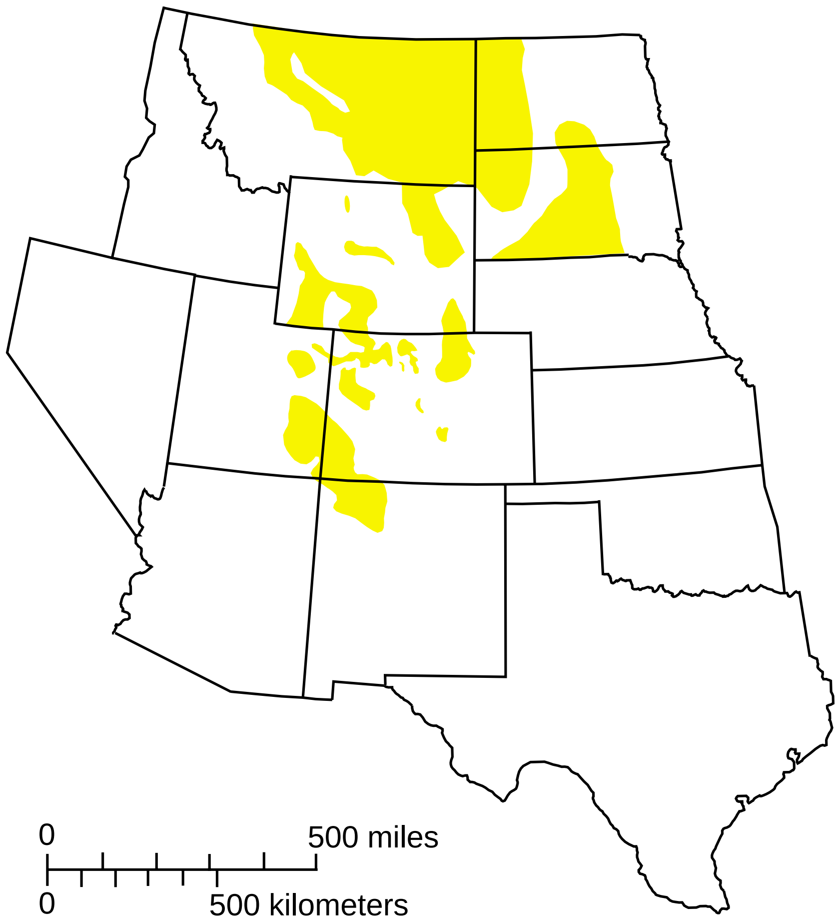



Figure 16. Areas having potential for continuous-type gas production, exclusive of coalbed methane (USGS Circular 1118, 1995)

## EXPLORATION POTENTIAL

Based on assessments made by various entities (Table 1 and Appendix) and our own exploration optimism, we believe the following situations offer significant opportunity for future discoveries of oil and gas in the Greater Rocky Mountain Region:

### Continuous-type Accumulations, Including Deep-Basin and Shallow Tight Gas Reservoirs

Prospective regions for discoveries in this category are shown in Figure 16. Areas shown in the Northern Great Plains of Montana, North and South Dakota include shallow Upper Cretaceous tight sandstones and chalks that are not considered as deep-basin accumulations. (Rice and Shurr, 1980; Rice and Spencer, 1995) Estimates of undiscovered technically recoverable biogenic methane from the sandstones are as high as 91 TCF (Dyman and others, 1995). Exploration and development for this resource beyond a few fields on pronounced uplifts has been hampered by the difficulty in recognizing productive intervals and areas and the lack of pipeline infrastructure (Hester, 1999).

Prospective deep-basin accumulations containing tight sand reservoirs (also shown in Figure 16), are presently known to exist in the Cretaceous section of most of the Laramide Rocky Mountain basins where burial has been sufficient to cause generation from available source rocks. This setting offers, perhaps, the greatest potential for discovery and development in the entire GRMR.

Although general areas of deep-basin accumulation have been identified, most development to date has been within so-called “sweet spots”. Other sweet spots remain to be discovered. More importantly, new technology is being developed to economically exploit lower-grade reserves redefining a “sweet spot”. Such advancement greatly expands the gas resource base.

### Coal Bed Methane

The development of coal bed methane has been one of the most significant and ongoing plays developed in the last few years (Schwochow, 1991; Murry and Schwochow, 1997; Schwochow and Murry, 1999). The largest area of development has been in Fruitland coals of the San Juan Basin (Fussett, 1998); however, several other areas continue to experience exploration and development and there will undoubtedly be future plays resulting in the establishment of significant resources (Scott, 1999).

The distribution and rank of coals within the GRMR and the volumes of in-place gas they are estimated to contain are shown in Figure 17. The distribution of rank in shallow coals in part appears to be influenced by proximity to igneous activity associated with the Rio Grande Rift. In general, higher rank coals have the capability of thermally generating and storing larger amounts of gas; however, the importance of biogenic gases in lower rank coals must also be considered. Major plays could be developed wherever sufficient gas saturation and productive capacity is found. A large part of the estimated deep in-place coalbed methane resource is in low-permeability coals that are not currently economically exploitable. Technology may be developed that would enable economic production to be established in this setting.

### Compartmented and Thin Oil Reservoirs

Many recognized pay zones have been encountered that do not permit establishment of economic production rates because of limited drainage area due to reservoir heterogeneity or because pays which do contain potentially economic permeability are too thin. Horizontal drilling techniques have proven successful in commercially developing these resources in some but not all areas. There appear to be many areas where horizontal drilling has not been tried, and considerable opportunity for developing reserves by this method may exist. An example will be discussed later in this paper.

### Fractured Oil-bearing Reservoirs

Fractured reservoirs have long been of historical significance in the GRMR. Established fracture production is widely scattered and found in several different formations, including: a) Lower Tertiary Green River and Wasatch Formations, in the Uinta Basin (Lucas and Drexler, 1975, 1976; Narr and Curry, 1982), b) Cretaceous Niobrara Formation and its equivalents in the Denver, Powder River, North Park, Piceance and San Juan Basins (Vincellette and Foster, 1992; Sonnenberg and Weimer, 1993), c) Pennsylvanian black shales in the Paradox Basin (Hite and others, 1984), and d) the uppermost Devonian and lowermost Mississippian Bakken Formation in the Williston Basin (Meissner, 1974; LeFever, 1991; Hansen and Long, 1991). All of these occurrences represent indigenous accumulations in or adjacent to mature source rocks. Many occur in deep-basin settings and are associated with generation overpressure. Historically, most of the early production was established in vertical wells and many of these wells were sub-economic, and offset well success was unpredictable.

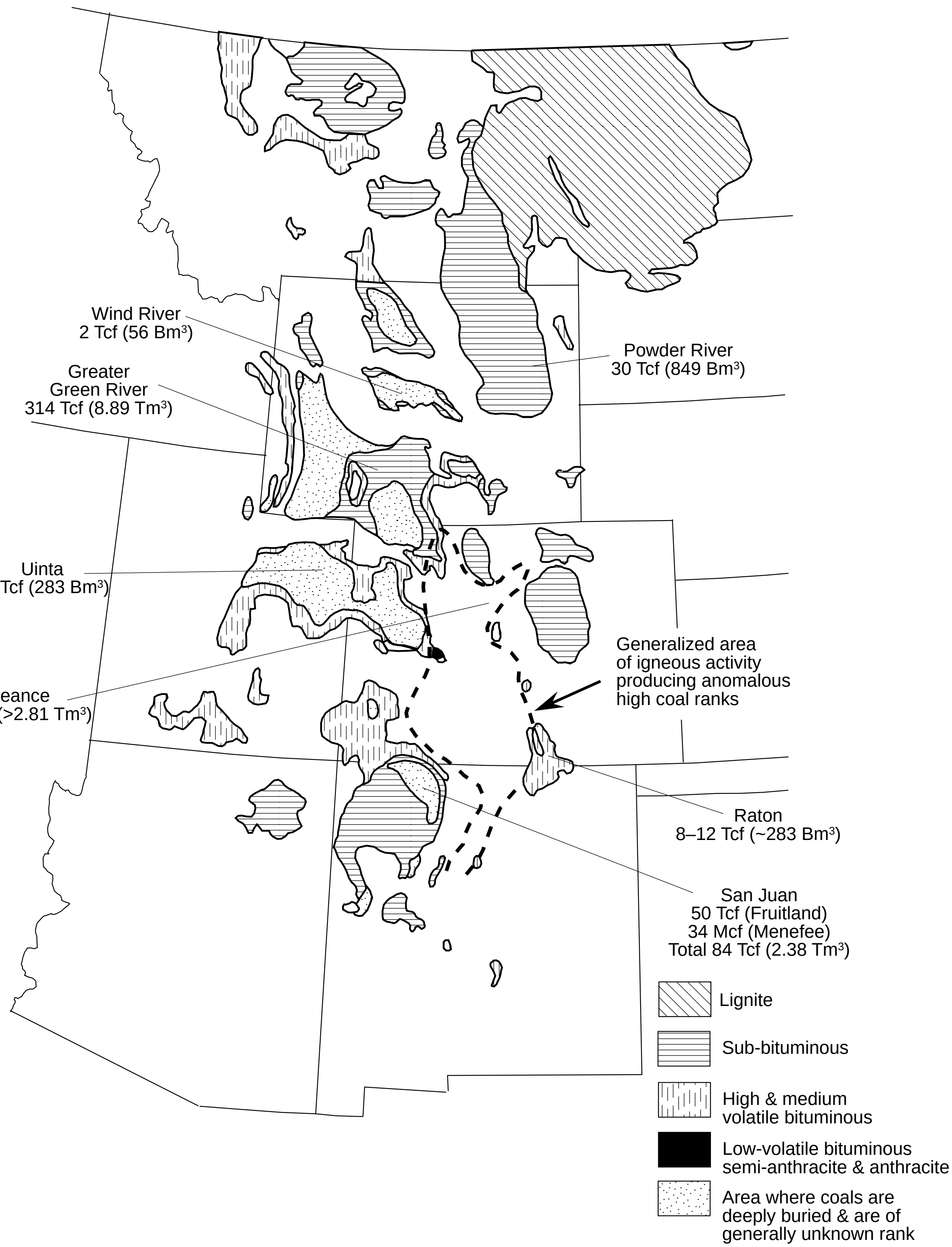



Figure 17. Major coal basins in the Greater Rocky Mountain Region with an assessment of rank at shallow depths and estimated contained volumes of gas (after Meissner, 1984, and Scott, 1999)

In the last few years, the industry has made considerable progress in evaluating, predicting and exploiting the occurrence of fractured reservoirs (Hoak and others, 1997; Hoak, 1998; Nelson, 1998). Development efforts utilizing horizontal drilling techniques (Figure 18) have been successful in a) the Niobrara Formation at Silo Field in the Denver Basin (Montgomery, 1991a, 1991b; Campbell and others 1992), b) the Cane Creek Shale in Bartlett Flat Field in the Paradox Basin (Morgan, 1992a, 1992b, Grummon, 1992) and c) the Bakken Formation in the so-called "Fairway Trend" of the southern Williston Basin (LeFever, 1991, Hansen and Long, 1991) where over 200 wells have been drilled since 1987.

## Confirmed Source Rocks With Little Or No Production

Cyclic black shales of Permian and Pennsylvanian age in the northern Denver Basin , Nebraska, have been identified as thin but very rich oil-prone source rocks (Clayton and King, 1984). Drilling in the area has encountered numerous oil shows and several small fields have been found. Carbonate reservoir permeabilities have generally been low and productive rates have therefore been marginal. Formation pressures are sub-normal and drilling with conventional overbalanced mud systems has undoubtedly caused formation damage. The area is under-explored in general. Additional drilling may find better reservoirs, and advanced drilling techniques may improve production rates. Horizontal drilling has been attempted, but has not yet been economically successful.

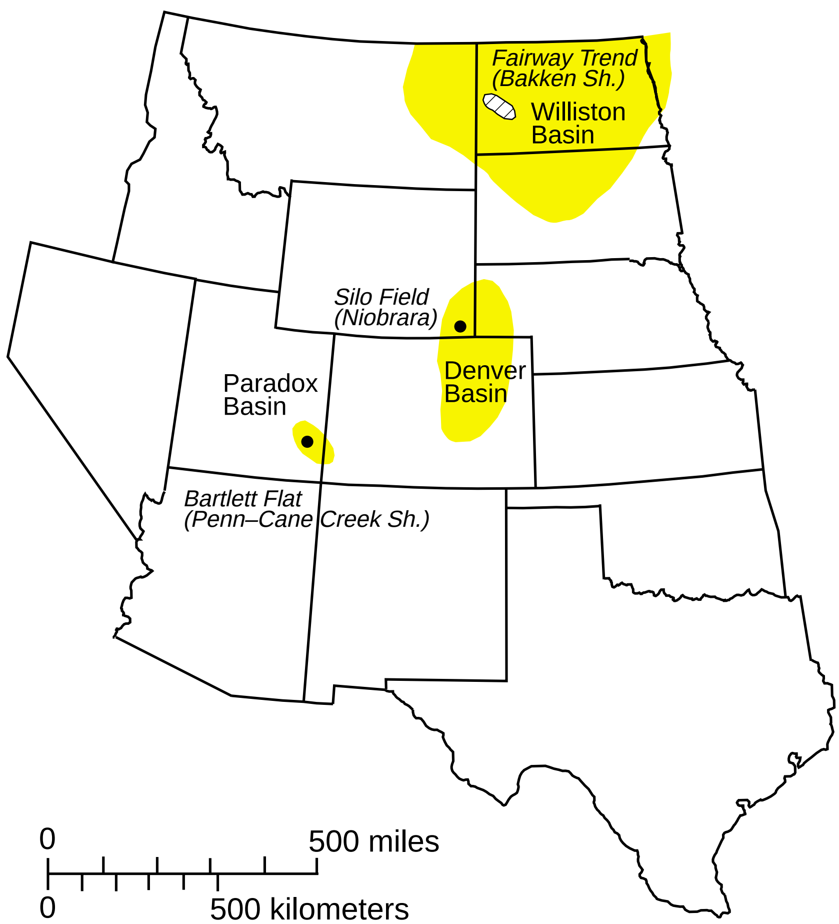



Figure 18. Areas where production from fractured source rocks has been established by horizontal drilling.

Excellent oil-prone source rocks are known to exist in Lower Paleozoic (Vinini, Woodruff, Pilot Shales), Middle Paleozoic (Chainman Formation Delle Member of the Woodman Formation) and Lower Tertiary (Sheep Pass, Elko Formations) sections present in the eastern Great Basin of western Utah and eastern Nevada (Poole and Claypool, 1984; Sandberg and Gutschick, 1984). Several small, but prolific, oilfields have been discovered; however, the richness and distribution of viable source rocks suggests that a large potential for future discoveries is present in the area. As an example, the Mississippian Chainman Shale penetrated in a deep well near the center of Railroad Valley Basin (Figure 21) was found to be 2454 ft (748 m) thick and to have an organic carbon content ranging from 1.0 to 5.2 percent, with an average of 2.7 percent (French, 1994). The Chainman section here is entirely within the oil window of generation maturity (vitrinite reflectance, Ro 0.8 at the top and 1.25 at the bottom), and maturity was achieved by burial during the relatively recent Basin and Range phase of structural development (Meissner, 1995). This evidence suggests a much larger potential for accumulation than has been found in related oil fields, which have established volumes of only 30 to 40 million barrels.

### Prospects Beneath Volcanic or Overthrust Cover

Several large areas in the GRMR contain Middle to Upper tertiary and Quaternary extrusive volcanic rocks that cover an underlying prospective sedimentary section (Figure 2 and 3b, 3c, 3d). These include the following volcanic “fields”: a) San Juan (southwest Colorado, see Gries, 1985, 1989), b) Northwest Wyoming, c) Marysvale (central Utah), d) Snake River Downwarp (southern Idaho) and d) certain areas of the Basin and Range (western Utah, eastern Nevada, southern Arizona and New Mexico). Although the underlying sedimentary section may contain viable petroleum systems, exploration has been hampered by the masking nature of the volcanics and the general inability of existing seismic techniques to see through it. Ability to prospect in these areas may depend upon newly developing technology.

The margins of many of the Rocky Mountain Laramide basins are characterized by high angle thrust faults that hide underlying structure (Figure 2, 3d, 3e, see Gries, 1983). Closed anticlines may exist and, the faults themselves may provide a sealing element to upturned beds or structural noses. There are several examples of oil and gas fields beneath these faults, including the recently discovered Cave Gulch Field (discussed later).

## APPLICATIONS OF NEW TECHNOLOGY

The application of new technology has been an important element in discovering and establishing new oil and gas reserves in the GRMR. Many recent developments have been made in areas where the presence of hydrocarbon saturation was known, but could not be economically produced with then existing capabilities. Considerable effort is currently being made to develop new concepts, techniques and abilities in almost every category that effects exploration, development and production (Crow, 1996; Coalson and others, 1997). These developments have been so extensive and pervasive that we will present only a short summary of those we consider to be of the most significance.

### Basic Geology

Constant advances have been made in understanding basic petroleum geology both as a fundamental science applicable on a global scale as well as to specific regional cases. As applied to the Greater Rocky Mountain Region, these include such items as: a) structure (Barrs and Stevenson, 1981; Powers, 1982; Gans and Miller, 1983; Stone, 1993; Koberl and Anderson, 1996), b) stratigraphy (Weimer, 1988; Dolson, 1994), c) source rock presence and maturity (Woodward and others, 1984), and d) reservoir development and behavior (Weimer, 1988; Goolsby and Longman, 1988; Coalson, 1989; Dolson, 1994; Slatt, 1998a, 1998b; Kuskraa, 1999). The latter is directly related to the development of both Cave Gulch and Jonah gas fields (discussed later in this paper) where the understanding of limited drainage of thick, stacked pay intervals is important.

## Seismic Techniques

The use of modern seismic acquisition and seismic techniques has had a profound influence on exploration and development in recent years (Gries and Dyer, 1985; Ray, 1995; Rocky Mountain Association of Geologists, 1996, 1997, 1998, 1999). Because most Rocky Mountain reservoirs have low porosity, "bright spot" phenomenon have not been notably successful in directly identifying hydrocarbon accumulations. However, high-frequency, 2-D, 2-D swath and 3-D methods, coupled with an enhanced understanding of how reflection amplitude, anisotrophy, character, interval velocity, and attitude represent geologic conditions of structure and stratigraphy, have resulted in numerous successful discoveries. Unusual or complex structures, such as overthrust areas, shear zones, and meteor impact features, have been interpreted through the use of analog geologic models. Similarly, reefs, mounds, channels and other stratigraphic features have been identified. The current and ongoing advances in seismic technique and interpretation will have a great impact on future exploration and development.

## Data Management

The thousands of wells drilled in the GRMR have generated an extremely large amount of basic geologic and engineering data. Modern computer techniques have-been and are still-being developed to sort, analyze, and plot this large volume of information. This continuing development will undoubtedly aid in identifying exploration prospects and development projects.

## Drilling, Evaluation, Completion

Advances in well drilling, evaluation and completion technology have had a significant impact in exploration and development. Horizontal wells offer great promise for exploiting reservoirs that are thin, have low permeability, are compartmentalized, are fractured, or contain viscous oil . Although the chief application of horizontal drilling in the Rocky Mountain Region has been in developing fractured reservoirs, opportunity exists in many other reservoir types and conditions (Lacy and others, 1992; LeFever, 1992; Schmoker and others, 1992; Nydegger, 1992; Armeteis and Hall, 1997). Many Rocky Mountain reservoirs are substantially underpressured and have been penetrated with wells utilizing standard, but overbalanced, mud systems. Many of these reservoirs have undergone extensive reservoir damage that can be minimized by drilling with recently-developed underbalanced mud and flow control drilling systems. Utilization of downhole motors and slim hole drilling has lowered drilling expenses and increased profits in the Denver Basin and made some uneconomic reservoirs viable development targets.

The development and use of formation imaging logs has aided the identification of depositional and structural features (Bourke and others, 1989; Serra, 1989; Seiler and others, 1990). These logs have proven especially useful in the evaluation of fractured reservoirs. Better understanding of log behavior in low-resistivity low-contrast formations has lead to better evaluation of potentially productive intervals in new or existing wells (Dolly and Mullarky, 1996).

Hydraulic fracturing of low-permeability reservoirs in the Rocky Mountain area has produced economic production rates Considerable progress has been made in designing less expensive and more efficient techniques, and improvements continue. Hydraulic fracture stimulation has proven successful in coalbed methane development (Ely and others, 1988). Cavity enlargement ("cavitation") has also proven to be a viable technique for enhancing coalbed methane production (Palmer and others, 1992)

## POLITICAL AND ECONOMIC CONSIDERATIONS

Although the potential for discovering and developing substantial reserves in the Greater Rocky Mountain Region obviously exists, whether or not it will occur in the future is heavily dependent on political and economic conditions. Agricultural areas are generally privately owned, but may have government mineral rights and a number of potentially productive areas are Native American tribal lands. Much of area is public land, administered by the Bureau of Land Management (BLM) or the U.S. Forest Service (USFS). Some potentially prospective regions, have been excluded from exploration as designated wilderness, or national parks and monuments (e.g., northern Montana Thrust Belt, Escalante-Grand Staircase area of the Colorado Plateau. in southern Utah). Additionally, environmental restrictions and areas containing protected and endangered animal and plant species limit access and operations.

### The Resource Pyramid

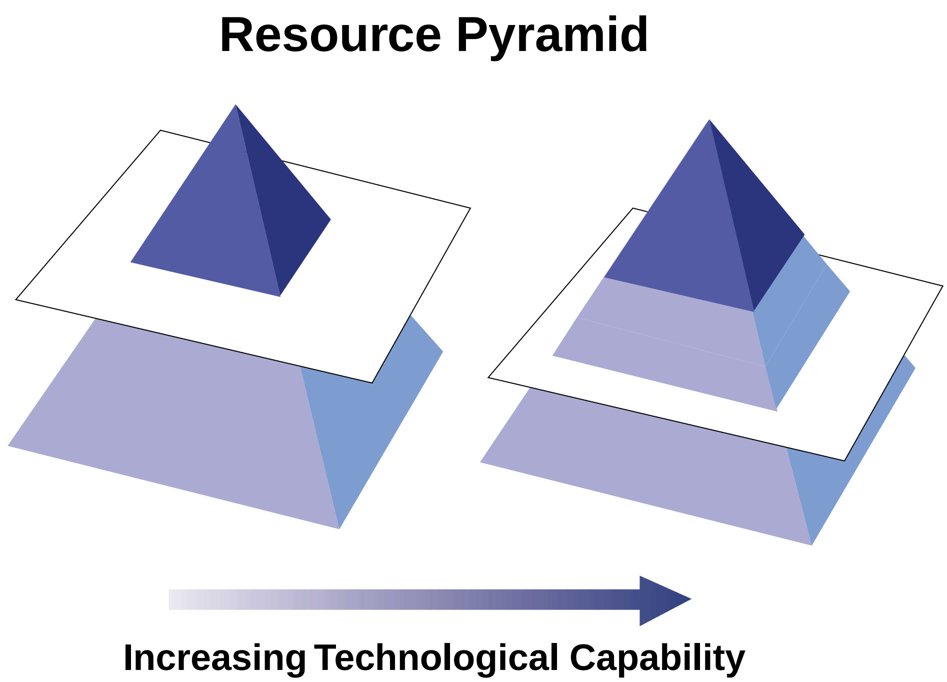
The concept of a resource triangle applied to an assessment of the economic viability of existing petroleum deposits was first proposed by Masters (1979). It was subsequently adapted by Thomasson (1982) and modified by Kuuskraa and Schmoker (1998) into a resource pyramid, as depicted in Figure 19. The apex of the pyramid represents a relatively small amount of oil or gas in very rich easily found and exploited fields that have highly favorable economics. Most of the total available resource lies in the lower portion of the pyramid in leaner and less-easily found and exploitable accumulations associated with poor or unprofitable economics. At any given time, the ability to move downward from the apex of the pyramid, depends on the product price and the finding and production costs. Increasing technical capability gives the explorationist and the exploitationist the ability to discover commercial oil and gas from leaner accumulations.

In the case of oil, several recent plays have been made that demonstrate the trend towards exploiting resources in the lower portion of the pyramid. Examples of this are production established from fractured reservoirs in 1) limestones in the Niobrara Formation at Silo field in the southeast Wyoming part of the Denver Basin, 2) shales and siltstones of the Bakken Formation “Fairway Trend” in the North Dakota part of the Williston Basin and 3) shale in the Cane Creek Member of the Paradox Formation in the Paradox Basin of eastern Utah. All of these examples represent basin-center- type accumulations developed in mature source rocks which were probably fractured by overpressures developed during active generation. Fractured reservoirs in the Bakken and Cane Creek are substantially overpressured; those in the Niobrara at Silo Field are slightly underpressured.

We see very significant additional opportunities for these type plays in the San Juan, Uinta, Powder River, Denver, Paradox, Williston, and many of the Basin and Range basins.

Part of the reason major oil companies failed in their most recent (mid-1980’s) attempt to explore and exploit the Rocky Mountain Region is that most of the reserves remaining to be discovered are in unconventional settings and the technology to take advantage of them had not yet been developed. Thus an opportunity exists in the Region today. For example, horizontal drilling technology has developed sufficiently to allow many accumulations in fractured, thin, or compartmentalized reservoirs to be exploited commercially. With further technological advances of all kinds, an increasing volume of rock will become attractive for effective exploration and economic exploitation.

The shape of the resource pyramid shown in Figure 20a clearly describes a much larger potential resource base than that shown in Figure 20b, i.e., the volume to height ratio is greater in 20a and increases exponentially downward from the apex. Because of the extremely large coalbed gas resources (Figure 17) and the abundance of basin centered or continuous-type oil and gas accumulations (Figures 12 and 16) that are generally associated with large, but poor-quality accumulations, the Rocky Mountain Region is best a)




b)

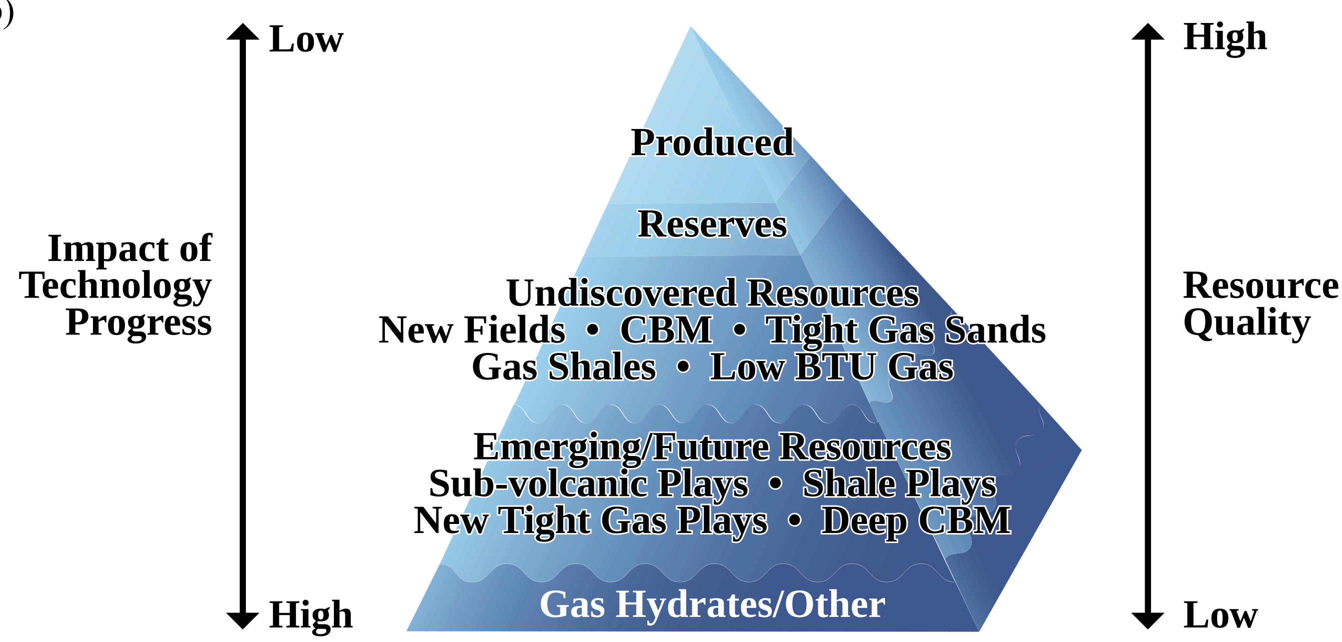



Figure 19. Resource pyramids a) pyramid showing amount of recoverable resource as a function of technological capability to exploit the resource. b) resource pyramid for gas in the Greater Rocky Mountain Region showing 1) the position of major future exploration potential with respect to reservoir types and plays, and their relation to 2) resource quality and, 3) the impact that future technology may have on the ability to exploit the available resource.

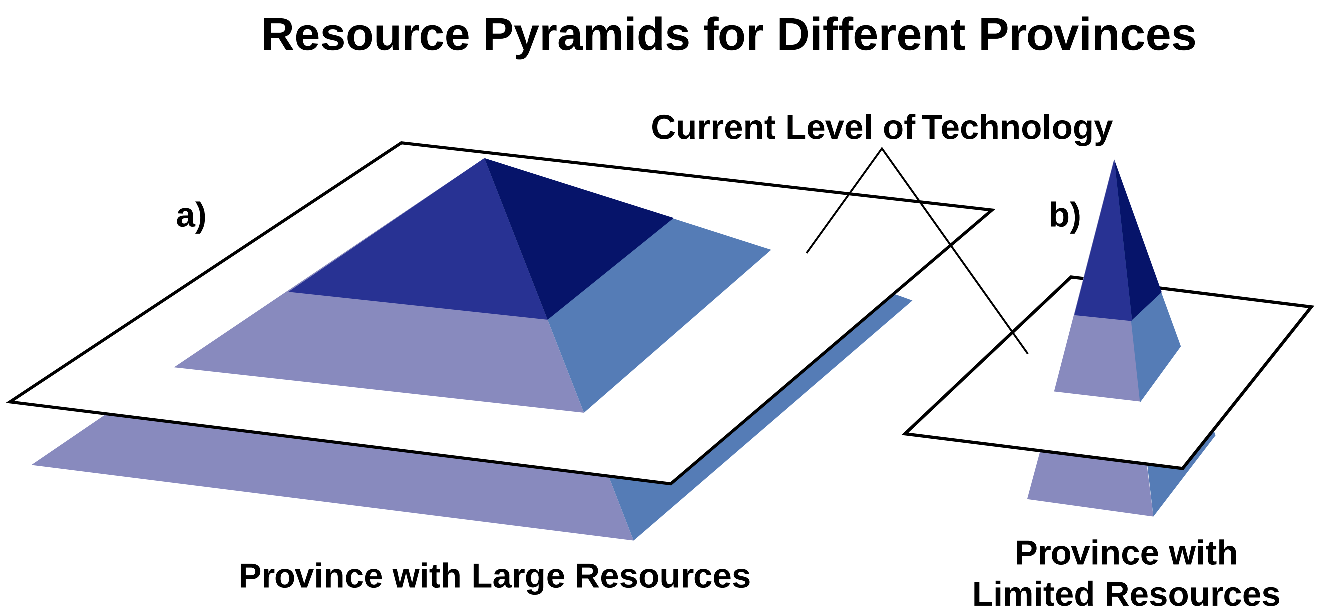



Figure 20. Resource pyramids with different base dimensions. a) Pyramid with large amount of lower quality resource. This type of pyramid is considered representative of the Rocky Moutnain Region. b) Pyramid with small amount of low-quality resource. This pyramid is considered to be representative of many of the world's productive areas.

characterized by the middle portion of the much broader pyramid of Figure 20a. A position in the middle of the broader pyramid is highly favorable for exploiting large reserves, providing technology for doing so is available and economic considerations are favorable. Most of the oil and gas postulated by the USGS to be technically available for future exploration and exploitation is contained in what they term "unconventional" continuous-type accumulations that occur in the middle part of the broader resource pyramid. These accumulations are generally characterized by "tight" matrix porosity and/or fractured reservoirs, anomalous pressures, large areas of complete hydrocarbon saturation and coalbed methane.

## EXAMPLES OF RECENT SIGNIFICANT DISCOVERIES —ANALOGS FOR THE FUTURE:

Although an assessment of the resource pyramid appropriate for the Greater Rocky Mountain Region demonstrates a basis for predicting a large amount of potentially discoverable and exploitable hydrocarbon resources, further evidence justifying this prediction may be based on the recent history of exploration and development, wherein five "giant" fields containing over 100 MMBO or 1 TCFG have been discovered (in most cases rediscovered) in the mid-to late-1990's, largely through the application of new technology. These include 1) an oil field with a hydrodynamically-tilted oil-water contact localized in a thin pay on the flank of a large regional anticline (Cedar Hills Field, Williston Basin), 2) an overpressured gas field where reserves were derived from an underlying and downdip regional basin center accumulation (Jonah, Green River Basin), 3) a field containing thick columns of gas and condensate localized in a complex anticline hidden beneath a thrust plate (Cave Gulch, Wind River Basin), 4) a coalbed methane field containing a mix of thermal and biogenic gas in a hi-volatile coal (Greater Drunkard's Wash, western Uinta Basin) and 5) a coalbed methane field containing biogenic gas in a lignite (Tongue River coals, Powder River Basin). Details relating to geologic concepts and applied technology that led to the discovery or re-development of these fields are described in the following sections.

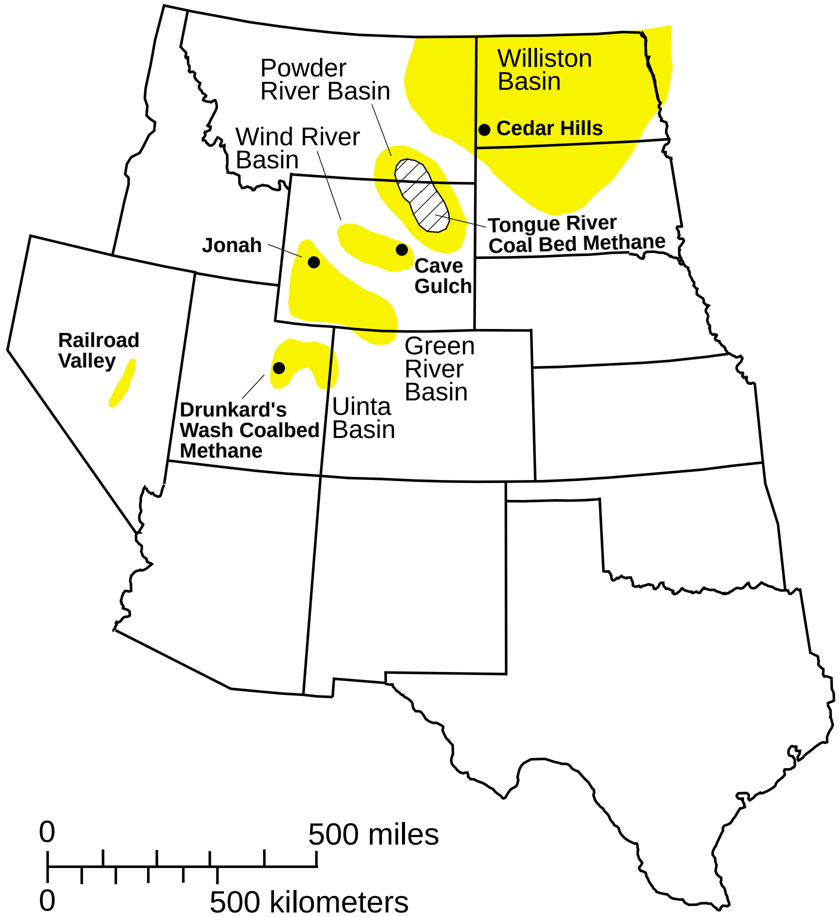



Figure 21. Map showing locations of recent major oil and gas discoveries that may serve as examples of the potential for discovery of future accumulations which may be found in the Greater Rocky Mountain Region.

## Cedar Hills Oil Field

One giant oil field has been "discovered" in the Ordovician Red River "B" zone in the Williston Basin. Cedar Hills is a conventional reservoir but with a somewhat unconventional hydrodynamic trap. The oil at Cedar Hills field is being exploited using the same or similar horizontal drilling technology to that applied to the unconventional fractured oil reservoirs described above (Montgomery, 1997). Here the reservoir is a thin porous interval that had previously been penetrated by several completed and abandoned oil wells that were associated with non-economic rates of production. A porous interval (the Ordovician Red River "B" zone) is somewhat variable in thickness and extends over a very large area where the oil is hydrodynamically trapped. As in all the individual cases we discuss in this paper, the reservoir had been drilled through and in this case had been completed non-commercially several times.

Figure 22a shows the drilling status prior to 1995 for the North Dakota portion of Cedar Hills field. Figure 22b shows the approximate outline in the same area of the newly horizontally exploited Red River "B" zone. Approximately 170 horizontal wells have been drilled, resulting in 150 productive completions ranging in true vertical depth from 8800 to 9500 ft. The total estimated ultimate recovery is now expected to be greater than 130 million barrels of oil.

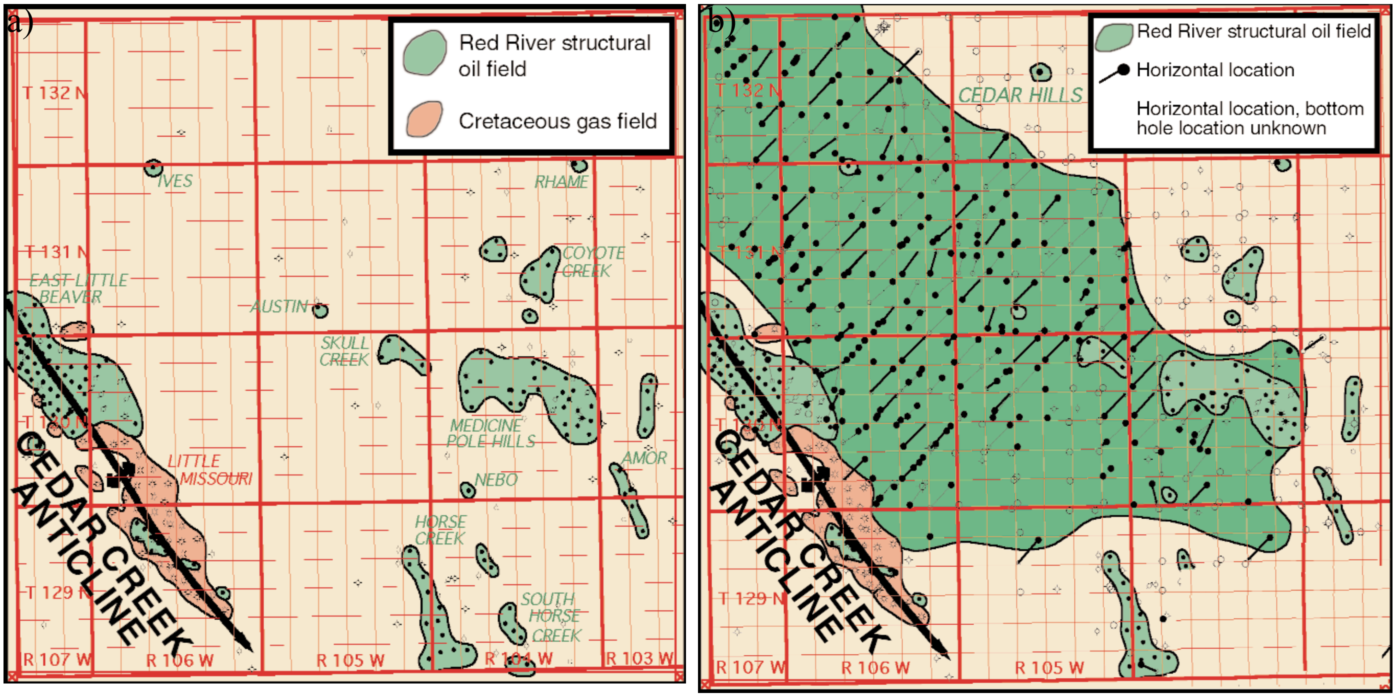



Figure 22. Cedar Hills Field, Williston Basin, Bowman County, North Dakota. Productive area and well penetrations: 1) before 1995; b) 1995 to Present. The EUR added since 1995 is greater than 100 MMBO.

## Jonah Gas Field

Jonah Gas Field is a somewhat unique structurally controlled sweet spot within the basin centered gas area of the Green River Basin of Wyoming (Warner, 1997, 1998). By year end 1999 it will contain over 150 wells with a per well average producible reserve of between 6 to 7 BCFG (personal communication with Ed Warner and Snyder Oil Company). Figure 23a shows the situation at Jonah Field in 1993. The field was first "discovered" in 1975 by the Davis Oil - Wardell Federal #1 which had an initial flow rate of 303 MCFGPD and 2 BOPD. It was later (1985) rediscovered by the Home Petroleum - Jonah Federal #1-4, which was tested for an initial rate of 470 MCFGPD. It was again rediscovered in 1993 by the McMurry Oil - Jonah Federal #1-5 which was tested for an initial rate of 3.7 MMCFGPD and 40 BOPD. The increase in production rates is attributed to improved technology in the form of better stimulation techniques. Completion technology continues to improve so that today a pay section similar to that found in the McMurry Oil - Jonah Federal #1-5 , the initial rate might be 10 to 12 MCFGPD. The average estimated ultimate recovery (EUR) per well was 2 BCF before 1994. Improved frac technology has raised the EUR steadily since 1992. For 1997 it was 6.7 BCF (Esphahanian et al., 1998). The current configuration of the field is shown in Figure 23b.

Current development has not yet established the eastern limit of the Field, and a recent stepout by Amoco has extended production more than four miles. Jonah Field has a gas column of approximately 3000 feet. Gas is trapped laterally and updip by a set of shear zones that raise a geopressured "sweet spot" some 3000 feet stratigraphically high to the top of regional deep-basin type overpressuring, with essentially no vertical displacement of the main reservoir section.

The shear zones that seal the "sweet spot" both laterally and updip originate in the basement and have almost no vertical throw. However, the field itself is highly broken by faults which control anomalous overpressure displacements of as much as 600 feet in separated fault blocks within the field. This extensive internal

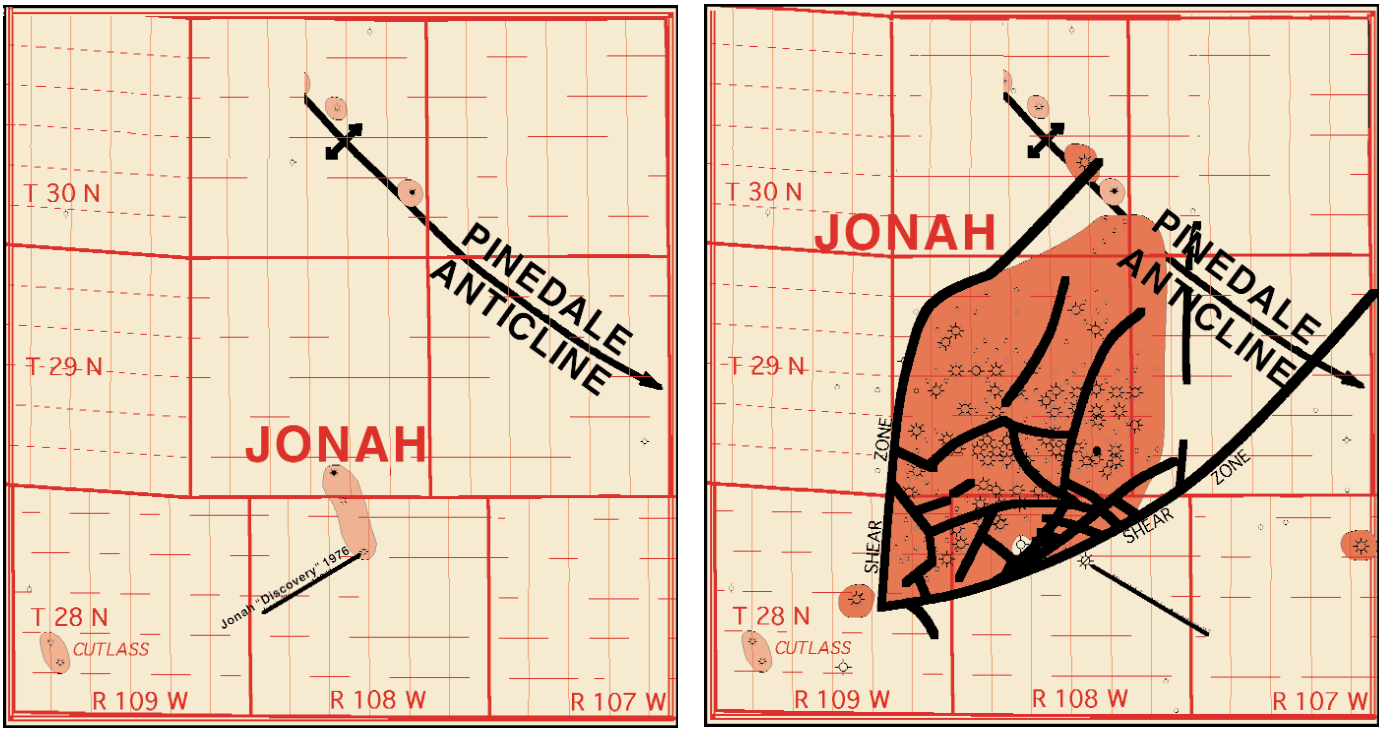



Figure 23. Jonah Field, Green River Basin, Sublette County, Wyoming. Productive area and well penetrations: a) before 1993; b) 1993 to Present. The EUR added since 1993 is greater than 1 TCFG.

faulting and fracturing has allowed gas to migrate vertically upward through tight rocks to a shallower reservoir, which has experienced less diagenesis and thus has higher porosity than is present in the underlying sediments associated with source rock gas generation. Current development indicates a recoverable volume of at least 1 TCFG. The field appears to have as much as 12 to 18 TCFG in place (Personal communication, Ed Warner). Anticipating a 30% recovery, it can reasonably be estimated that ultimate production may amount to as much as 3 to 5 TCFG.

## Cave Gulch Gas Field

The locations and status of wells drilled in the Cave Gulch - Waltman area of the Wind River Basin in Wyoming prior to 1994 are shown in Figure 24a. The area may ultimately contain more than 1 TCF of new gas reserves added since 1994, primarily because of a different geologic concept, understood by Larry McPeek, the originator of the project that led to the rediscovery and new development. McPeek recognized that even though Cave Gulch was a relatively small structural closure under the Owl Creek thrust plate, the fluvial depositional regime of the Ft. Union (Lower Tertiary) and Lance (uppermost Cretaceous) formations would allow stacking of a very thick package of sands containing complexly compartmentalized reservoirs and very limited drainage areas, allowing tight spacing and multiple twins. For instance, in one 160 acre area there are 14 wells completed and 2 locations. In addition, the deeper sands, which had proven to be "non-commercial" in wells drilled prior to 1994 were recognized by McPeek to be prospective on paleostructural highs, where early gas accumulation should reduce or eliminate the diagenetic destruction of reservoir quality in deeper reservoirs. New fracturing technology has also played a significant role in successfully stimulating these deeper zones.

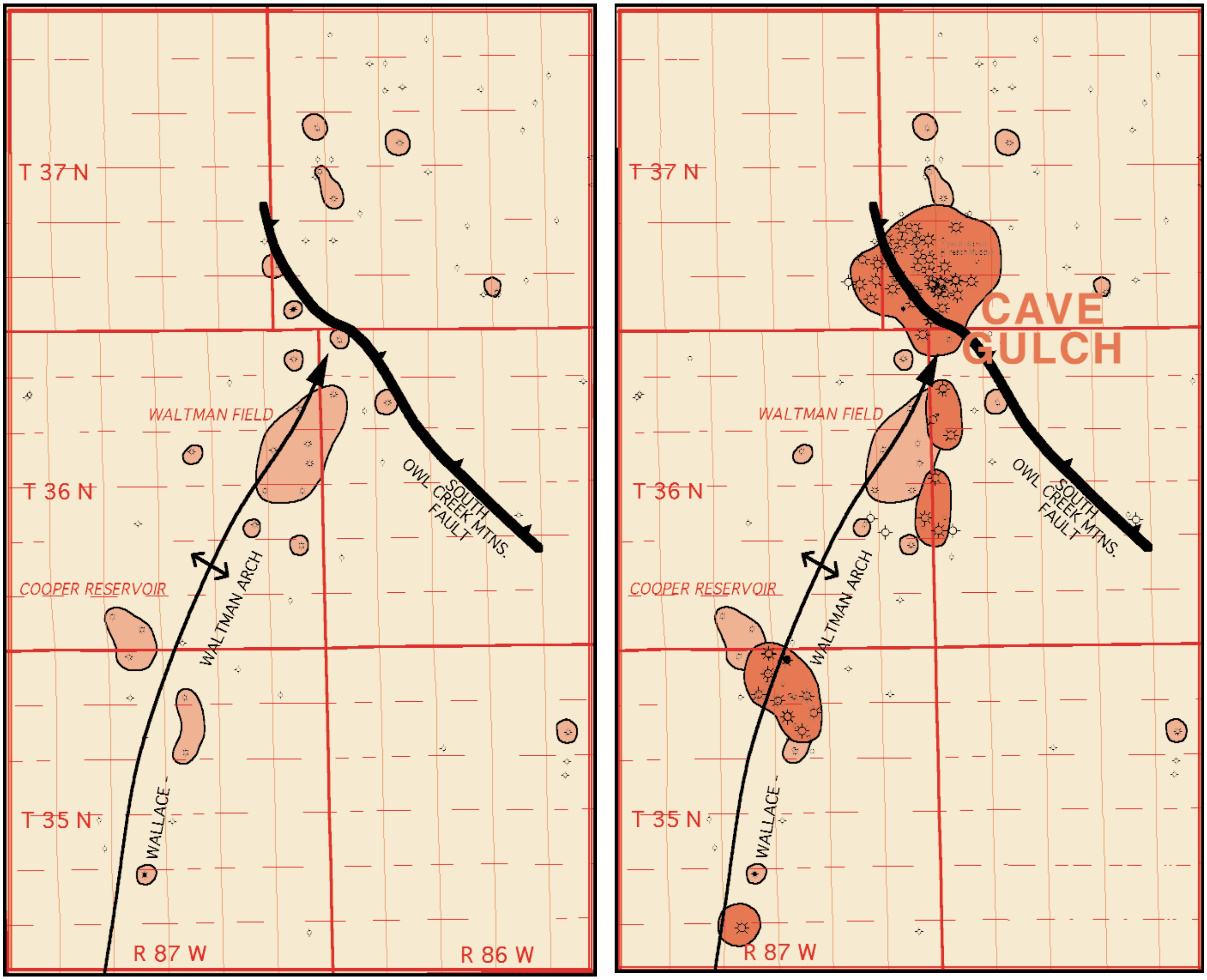



Figure 24. Cave Gulch Field, Wind River Basin, Natrona County, Wyoming. Productive area and well penetrations: a) before 1994; b) 1994-Present. The EUR added since 1993 is greater than 1 TCFG.

Since 1994, Cave Gulch Field has had some forty-eight shallow (3,000 to 10,000 feet) wells and six deep (17,000 - 19,000 foot) wells drilled (Figure 24b). Current development has established a maximum NET pay section of approximately 1300 feet. One deep well blew out at calculated absolute open flow of 1 BCFGPD.

## Drunkard's Wash Coalbed Methane Field

Figure 25a shows the Greater Drunkard's Wash gas area prior to 1993. Today there are 240 wells producing with a drilling program of approximately sixty wells a year projected for the foreseeable future. In 1993 Buzzards Bench coalbed methane field had just one well. It now has over forty. It appears that the entire area between Drunkards Wash and Buzzards Bench Fields will eventually be continuously productive (see Figure 25b).

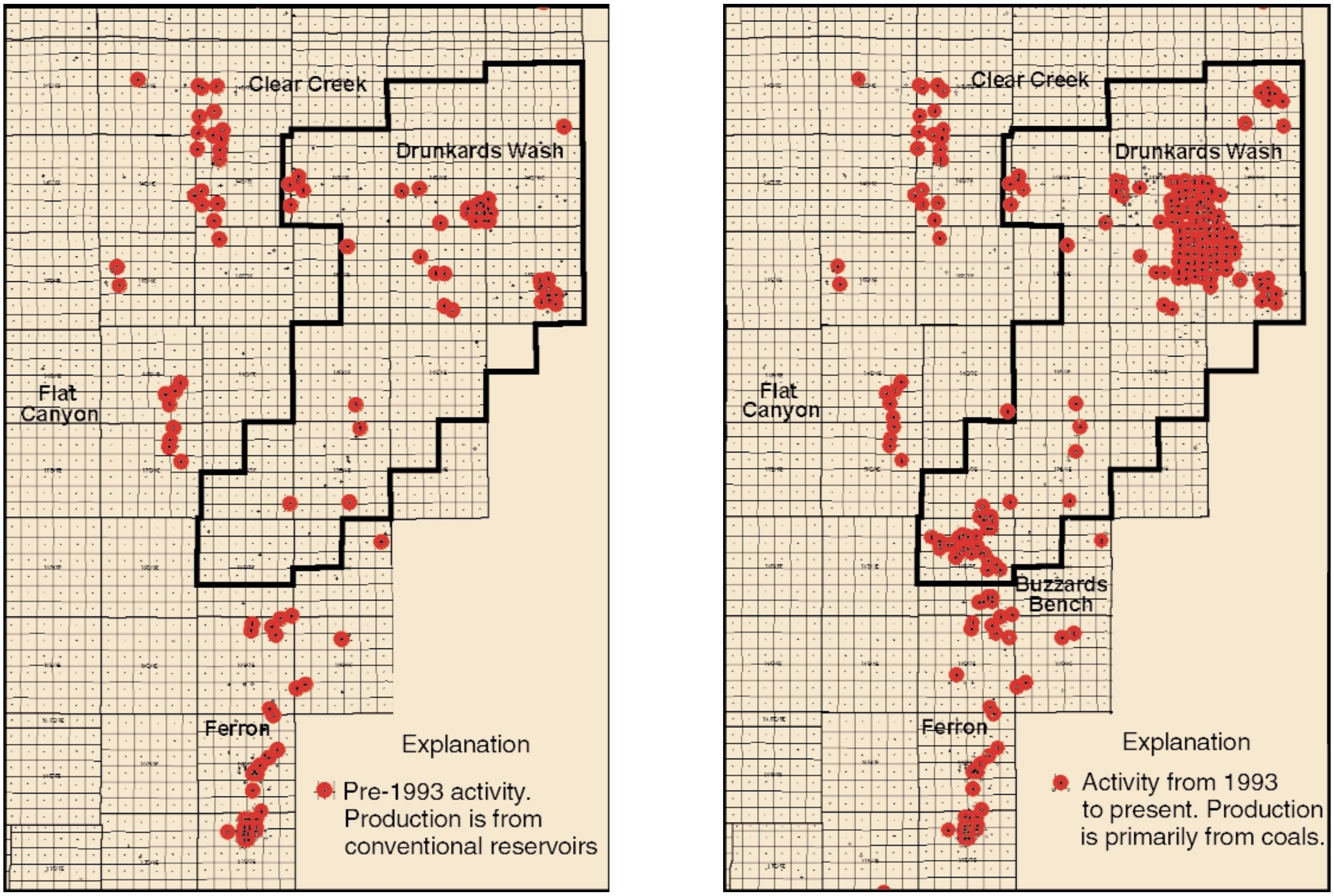



Figure 25. Drunkards Wash Coalbed Methane Field, Wasatch Plateau. Productive area and well penetrations: a) before 1993. Production shown is all from conventional sandstone reservoirs. b) 1993-Present. Added production is primarily from coals with an EUR of 1-3 TCFG.

According to Lamarre and Burns (1999), the average coal thickness in Drunkard's Wash Field is twenty four feet. One well that has been producing over five years from a twenty eight foot thick coal has a cumulative production of 3.5 BCFG and is currently producing 1461 MCFD and 369 BWPD. The first thirty three wells have produced for over sixty five months and their per well daily production averages just under 1 MMCFGPD and 85 BWPD. The average per well daily gas production has increased by 380% while water production has decreased by 80%. None of these wells has begun to decline after five and one half years of continuous production. Considering the current and projected number of development wells, it seems reasonable to assume that Greater Drunkards Wash area, including Buzzards Bench, may eventually contain as much as 3 TCFG.

## Powder River Basin Coalbed Play

Another coalbed methane giant gas field is being rapidly developed in the Powder River Basin. Figure 26a shows wells drilled prior to 1994 and Figure 26b approximates current well development. However, with forty one rigs running and plans in 1999 and 2000 for as many as 1000 wells a year, this play is in a state of explosive development. We can already be assured that this giant field developing in the Tongue River Coal Member of the Paleocene Fort Union Formation, which ranges from 300 to 1200 feet in depth, will be well over 1 TCFG. Estimates of as much as 7 to 12 TCFG have now been made (Montgomery, 1999).

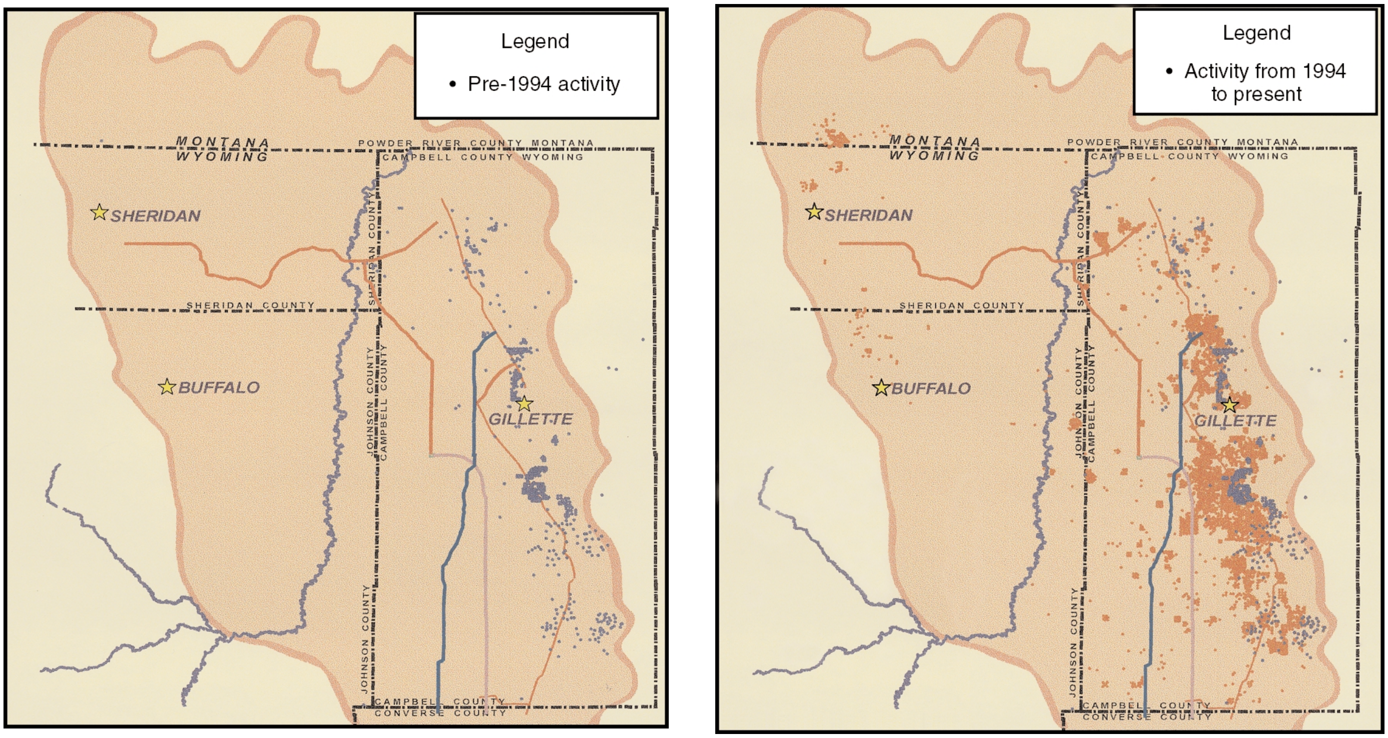



Figure 26. Powder River Basin Coalbed Methane development, Cambell, Johnson, and Sheridan Counties, Wyoming and Powder River County, Montana. Productive area and well penetrations: 1) before 1994; b) 1994 to Present. The EUR added since 1994 is greater than 1 TCFG. Basin potential is 7-12 TCFG.

## SUMMARY AND CONCLUSIONS

The Greater Rocky Mountain Region is a large geologically heterogeneous area containing numerous basins and uplifts. Although it contains a wide variety of structures that were generated at several different times, those that were produced in the Lower and Upper Tertiary are commercially the most significant. Sedimentary rocks representing certain time periods are absent in some areas; however, numerous oil-prone and gas-prone source rocks and prospective reservoirs ranging from Precambrian to Tertiary in age are present in one area or another, and these have contributed to the presence of a large number and variety of petroleum systems. Productive and prospective reservoirs include a spectrum of carbonates and sandstones containing matrix porosity and permeability, as well as fracture-type and coalbed methane reservoirs. Several investigating entities have estimated the potential for future producible hydrocarbon discoveries to be in the range of 10.4-15.4 BB of petroleum liquids and 192-260 TCF of gas.

Known hydrocarbon accumulations include those controlled by conventional structural, stratigraphic, and combination trap types that are often significantly affected by dynamic groundwater flow. Of particular significance to further exploration and development potential are a class of unconventional accumulations associated with pervasive regional hydrocarbon saturation, a general absence of moveable groundwater, and the presence of either abnormally-high or -low fluid pressures. These accumulations may be dynamic and transient in nature and commonly occur in low-permeability or fractured reservoirs associated with mature source rocks in the deeper parts of typical Rocky Mountain basins. Petroleum systems present in the Cretaceous and Lower Tertiary section will be major contributors to future hydrocarbon production, and gas will be of particular importance because of the large number of coal measures present. Gas generated by either thermal or bacterial processes is present in both coalbeds and in nearby sandstone reservoirs. Exploration and development opportunity is present in regions associated with confirmed high generation-capacity source rocks, but with little established production.

Much of the potential hydrocarbon resource remaining to be discovered and developed is characterized as representing the largest overall volume in the “resource pyramid”. The exploitation of this resource will depend heavily on the price of the product and the application of new and developing technology that will lower the cost of exploration and enable economically attractive development.

The presence of five large oil and gas fields that have been developed in the last six years may be taken as an indication of the type and magnitude of remaining resource type and potential. Most of these so-called “discoveries” represent hydrocarbon accumulations that were previously “known” through prior exploration, but had little economic significance until the development of geologic understanding, drilling, evaluation and completion technology rendered them economically viable.

APPENDIX

This appendix contains information on the amounts of oil and gas resources that may be found and developed in the Greater Rocky Mountain Region as estimated by various agencies.

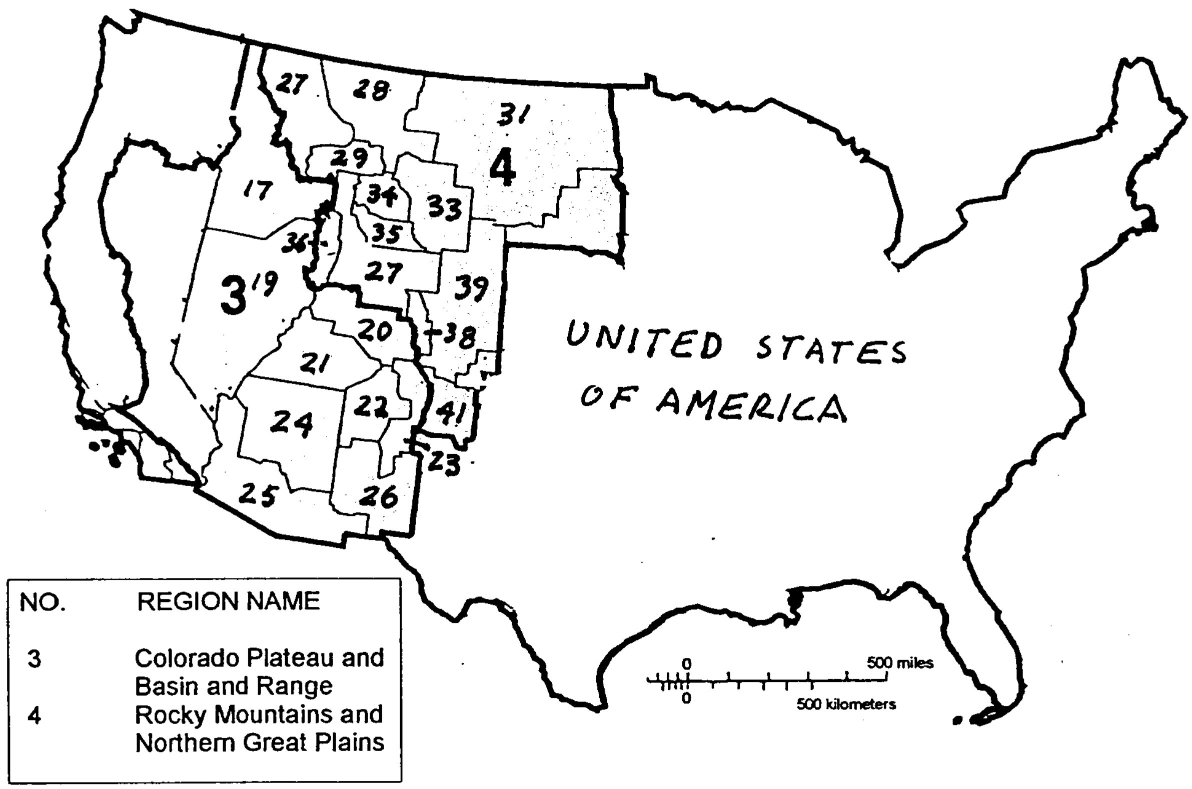



Figure A1. Index map of the US showing area of the Greater Rocky Mountain Region and its included geologic province boundaries as defined by the USGS (1995). Index numbers are keyed to province names in Table A1, A2 and A3

## TABLE A1
## USGS NAMES OF PROVINCES IN GREATER ROCKY MTN REGION

Province numbers keyed to map, Figure A1

| PROV. NO. | PROVINCE NAME | PROV. NO. | PROVINCE NAME |
|---|---|---|---|
| 17 | Idaho-Snake River Downwarp | 29 | Southwest Montana* |
| 19 | Eastern Great Basin* | 31 | Williston Basin, U.S.* |
| 20 | Uinta-Piceance Basin* | 33 | Powder River Basin* |
| 21 | Paradox Basin* | 34 | Big Horn Basin* |
| 22 | San Juan Basin* | 35 | Wind River Basin* |
| 23 | Albuquerque-Santa Fe Rift | 36 | Wyoming Thrust Belt* |
| 24 | Northern Arizona* | 37 | Southwestern Wyoming* |
| 25 | S. Arizona-SW New Mexico | 38 | Park Basins* |
| 26 | South-Central New Mexico | 39 | Denver Basin* |
| 27 | Montana Thrust Belt* | 40 | Las Animas Arch* |
| 28 | North-Central Montana* | 41 | Raton B.*-Sierra Grande Upl. |

* Provinces with oil and/or gas production

From Table 2, USGS Circular 1118, p 14

## TABLE A2
## KNOWN VOLUMES OF OIL, NGL & GAS WITHIN DESIGNATED GEOLOGIC PROVINCES OF THE GREATER ROCKY MOUNTAIN REGION

From Table I, USGS Open File report 97-463

| WORLD RANK | U.S. PROV.# | NAME | MEDIAN ESTIMATED VALUES | | | | % of RM Reserves | |
|---|---|---|---|---|---|---|---|---|
| | | | OIL (BB) | NGL (BB | TOT. LIQ. (BB | GAS (TCF) | TOT. LIQ. (BB | GAS (TCF) |
| 277 | 19 | E. Great Basin | 0.05 | 0 | 0.1 | 0.05 | 0.3 | 0.1 |
| 102 | 20 | Uinta-Piceance Basin | 1.6 | 0.1 | 1.7 | 4.7 | 10.0 | 5.9 |
| 164 | 21 | Paradox Basin | 0.6 | 0.1 | 0.7 | 0.9 | 4.1 | 1.1 |
| 50 | 22 | San Juan Basin | 0.3 | 1.4 | 1.7 | 38.2 | 10.0 | 47.8 |
| 300 | 24 | N. Arizona | 0.05 | 0 | 0.1 | 0.05 | 0.3 | 0.1 |
| 368 | 27 | Montana Thrust Belt | 0.05 | 0 | 0.1 | 0.05 | 0.3 | 0.1 |
| 163 | 28 | No-Cent. Montana | 0.5 | 0.05 | 0.6 | 2.3 | 3.2 | 2.9 |
| 283 | 29 | SW Montana | 0.05 | 0.05 | 0.1 | 0.2 | 0.6 | 0.3 |
| 98 | 31 | Williston Basin, U.S. | 2.1 | 0.2 | 2.3 | 2.4 | 13.5 | 3.0 |
| 88 | 33 | Powder River Basin | 2.8 | 0.2 | 3 | 2.6 | 17.6 | 3.3 |
| 92 | 34 | Big Horn Basin | 2.7 | 0.05 | 2.8 | 1.8 | 16.2 | 2.3 |
| 154 | 35 | Wind River Basin | 0.5 | 0.05 | 0.6 | 2.8 | 3.2 | 3.5 |
| 134 | 36 | Wyoming Thrust Belt | 0.2 | 0.7 | 0.9 | 4 | 5.3 | 5.0 |
| 77 | 37 | SW Wyoming | 0.8 | 0.4 | 1.2 | 16.3 | 7.1 | 20.4 |
| 312 | 38 | Park Basins | 0.05 | 0 | 0.05 | 0.05 | 0.3 | 0.1 |
| 123 | 39 | Denver Basin | 0.9 | 0.3 | 1.2 | 3.5 | 7.1 | 4.4 |
| 248 | 40 | Las Animas arch | 0.1 | 0.05 | 0.2 | 0.1 | 0.9 | 0.1 |
| | | TOTAL ROCKY MTN.: | 13.4 | 3.7 | 17 | 80 | 100.0 | 100.0 |
| | | TOTAL U.S.: | 171.7 | 29.4 | 201.1 | 908.6 | | |
| | | RM% OF TOTAL U.S.: | 7.8% | 12.6% | 8.5% | 8.8% | | |
| | | | OIL (BB) | NGL (BB | TOT. LIQ. (BB | GAS (TCF) | | |

17 RM AREAS NAMED IN '97 REPORT ARE PRODUCTIVE
18 ARE PRODUCTIVE COUNTING NEW GAS PRODUCTION THE RATON BASIN.
Retrieved from the Internet4/13/99
With World Rank and USGS World Province Number:
NOTE--5000 SUBTRACTED FROM WORLD PROV. NO. TO GIVE U.S. PROV. NO. OF 1985 ASSESMENT

TABLES A3a-e

UNDISCOVERED TECHNICALLY RECOVERABLE RESOURCES WITHIN DESIGNATED GEOLOGIC PROVINCES OF THE GREATER ROCKY MOUNTAIN REGION

**TABLE A3a**

ESTIMATES OF UNDISCOVERED TECHNICALLY RECOVERABLE CONVENTIONAL OIL, NGL, & GAS RESOURCES BY PROVINCE (USGS, 1995, TABLE 2, p. 12)

| PROV. # | PROVINCE NAME | OIL, BB F95* | OIL, BB F5* | OIL, BB MEAN | GAS, TCF F95 | GAS, TCF F5 | GAS, TCF MEAN | NGL, BB F95 | NGL, BB F5 | NGL, BB MEAN |
|---|---|---|---|---|---|---|---|---|---|---|
| 17 | Idaho-Snake Riv. Downwar | 0.00 | 0.01 | **<0.01** | 0.00 | 0.09 | **0.01** | 0.00 | 0.00 | **0.00** |
| 19 | Eastern Great Basin | 0.06 | 1.34 | **0.49** | 0.01 | 1.12 | **0.33** | 0.00 | 0.02 | **0.01** |
| 20 | Uinta-Piceance Basin | 0.04 | 0.59 | **0.21** | 1.94 | 9.56 | **4.54** | 0.01 | 0.21 | **0.07** |
| 21 | Paradox Basin | 0.11 | 0.61 | **0.31** | 0.93 | 3.48 | **2.02** | 0.03 | 0.17 | **0.09** |
| 22 | San Juan Basin | 0.07 | 0.29 | **0.16** | 0.52 | 1.53 | **0.98** | 0.01 | 0.04 | **0.02** |
| 23 | Albuquerque-Rio Grande R | 0.00 | 0.15 | **0.05** | 0.00 | 1.29 | **0.36** | 0.00 | 0.06 | **0.02** |
| 24 | Northern Arizona | 0.00 | 0.32 | **0.07** | 0.00 | 0.96 | **0.17** | 0.00 | 0.08 | **0.01** |
| 25 | S. Arizona-S.W. new Mexic | 0.00 | 0.06 | **0.02** | <0.01 | 0.53 | **0.20** | <0.01 | 0.05 | **0.02** |
| 26 | South-Central New Mexico | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | **0.00** | 0.00 | 0.00 | **0.00** |
| 27 | Montana Thrust Belt | 0.00 | 0.01 | **<0.01** | 0.00 | 8.53 | **1.93** | 0.00 | 0.03 | **0.01** |
| 28 | Central Montana | 0.13 | 0.42 | **0.27** | 0.04 | 1.37 | **0.84** | <0.01 | <0.01 | **<0.01** |
| 29 | Southwest Montana | 0.00 | 0.13 | **0.03** | 0.12 | 0.76 | **0.40** | <0.01 | 0.01 | **<0.01** |
| 31 | Williston Basin | 0.25 | 1.17 | **0.65** | 0.89 | 2.61 | **1.69** | 0.07 | 0.22 | **0.14** |
| 33 | Powder River Basin | 0.70 | 3.88 | **1.94** | 0.66 | 2.88 | **1.60** | 0.04 | 0.17 | **0.09** |
| 34 | Big Horn Basin | 0.08 | 0.87 | **0.39** | 0.24 | 1.19 | **0.62** | <0.01 | 0.02 | **0.01** |
| 35 | Wind River Basin | 0.05 | 0.32 | **0.16** | 57.00 | 2.21 | **1.24** | 0.01 | 0.02 | **0.01** |
| 36 | WyomingThrust Belt | 0.21 | 1.16 | **0.63** | 5.55 | 16.60 | **10.68** | 0.51 | 1.84 | **1.13** |
| 37 | S.W. Wyoming | 0.04 | 0.40 | **0.17** | 0.70 | 2.86 | **1.58** | 0.01 | 0.04 | **0.02** |
| 38 | Park Basins | <0.01 | 0.11 | **0.03** | <0.01 | 0.07 | **0.02** | 0.00 | <0.01 | **0.00** |
| 39 | Denver Basin | 0.09 | 0.42 | **0.23** | 0.34 | 1.38 | **0.75** | 0.01 | 0.04 | **0.02** |
| 40 | Las Animas Arch | 0.04 | 0.28 | **0.14** | 0.20 | 1.07 | **0.53** | 0.01 | 0.03 | **0.01** |
| 41 | Raton Basin-Sierra Grand U | 0.00 | 0.00 | **0.00** | 0.00 | 0.11 | **0.04** | 0.00 | <0.01 | **<0.01** |
| | **TOTAL:** | 3.72 | 8.93 | **5.93** | 20.70 | 43.88 | **30.53** | 0.95 | 2.59 | **1.68** |

*F95= 95% probability and *F5= 5% probability of the occurrence of at least the amount tabulated

**TABLE A3b**

TECHNICALLY RECOVERABLE RESOURCES ESTIMATED FOR CONTINUOUS-TYPE PLAYS IN SANDSTONES, SHALES AND CHALKS (USGS, 1995, TABLE 4, p. 18)

| PROV. # | PROVINCE NAME | OIL, MMB F95 | OIL, MMB F5 | OIL, MMB MEAN | GAS, TCF F95 | GAS, TCF F5 | GAS, TCF MEAN | NGL, MMB F95 | NGL, MMB F5 | NGL, MMB MEAN |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | Uinta-Piceance Basin | 59 | 139 | **94** | 11.55 | 23.38 | **16.74** | 63 | 139 | **96** |
| 21 | Paradox Basin | 61 | 139 | **242** | 0.05 | 0.48 | **0.19** | 0 | 0 | **0** |
| 22 | San Juan Basin | 68 | 597 | **189** | 10.66 | 36.84 | **21.15** | | 2 | **1** |
| 28 | Central Montana | 0 | 394 | **0** | 19.92 | 79.03 | **43.16** | 0 | 0 | **0** |
| 31 | Williston Basin | 97 | 283 | **167** | 0.08 | 0.24 | **0.14** | 0 | 0 | **0** |
| 37 | S.W. Wyoming | 0 | 0 | **0** | 55.95 | ##### | **119.30** | 810 | 3104 | **1733** |
| 39 | Denver Basin | 139 | 502 | **285** | 1.49 | 5.69 | **3.16** | | | |
| | **TOTAL:** | 520 | 1635 | **977** | ##### | ##### | **203.85** | 873 | 3244 | **1829** |

**TABLE A3c**

TECHNICALLY RECOVERABLE RESOURCES ESTIMATED FOR CONTINUOUS-TYPE PLAYS, IN COAL BEDS (USGS, 1995, TABLE 5, p. 19)

| PROV. # | PROVINCE NAME | GAS, TCF F95 | GAS, TCF F5 | GAS, TCF MEAN |
|---|---|---|---|---|
| 20 | Uinta Basin | 1.86 | 4.82 | **3.21** |
| 20 | Piceance Basin | 5.47 | 10.09 | **7.49** |
| 22 | San Juan Basin | 5.76 | 9.67 | **7.53** |
| 33 | Powder River Basin | 0.32 | 2.90 | **1.11** |
| 35 | Wind River Basin | 0.22 | 0.72 | **0.43** |
| 37 | S.W. Wyoming | 0.83 | 7.66 | **3.89** |
| 41 | Raton Basin | 1.39 | 2.23 | **1.78** |
| | **TOTAL:** | 18.97 | 33.59 | **25.44** |

TABLE A3 Continued

**TABLE A3d**

| SUMMARY OF TECHNICALLY RECOVERABLE RESOURCES DERIVED FROM U.S.G.S, 1995 ASSESSMENT | OIL, BB | | | GAS, TCF | | | NGL, BB | | |
|---|---|---|---|---|---|---|---|---|---|
| RESOURCE CATEGORY | F95 | F5 | **MEAN** | F95 | F5 | **MEAN** | F95 | F5 | **MEAN** |
| Conventional Resources | 3.72 | 8.93 | **5.93** | 20.70 | 43.88 | **30.53** | 0.95 | 2.59 | **1.68** |
| Continuous- Type-Ss,Sh, Carb. | 0.52 | 1.64 | **0.98** | ##### | ##### | **203.85** | 0.87 | 3.24 | **1.83** |
| Continuous-Type-Coal | | | | 18.97 | 33.59 | **25.44** | | | |
| **TOTAL:** | 4.24 | #### | **6.91** | ##### | ##### | **259.82** | 1.82 | 5.83 | **3.51** |

| | TOTAL LIQUID HC'S,BB* | | | GAS, TCF | | |
|---|---|---|---|---|---|---|
| | F95 | F5 | MEAN | F95 | F5 | MEAN |
| Conventional Resources | 4.67 | #### | 7.61 | 20.70 | 43.88 | 30.53 |
| Continuous- Type-Ss,Sh, Carb. | 1.39 | 4.88 | 2.81 | ##### | ##### | 203.85 |
| Continuous-Type-Coal | | | | 18.97 | 33.59 | 25.44 |
| TOTAL: | 6.06 | #### | 10.42 | ##### | ##### | 259.82 |

*OIL + NGL

**TABLE A3e**

| SUMMARY OF TECHNICALLY RECOVERABLE RESOURCES DERIVED FROM U.S.G.S, 1995 ASSESSMENT | TOTAL LIQUID HCs*, BB | | | GAS, TCF | | |
|---|---|---|---|---|---|---|
| RESOURCE CATEGORY | F95 | F5 | **MEAN** | F95 | F5 | **MEAN** |
| Conventional Resources | 4.67 | #### | **7.61** | 20.70 | 43.88 | **30.53** |
| Continuous- Type-Ss,Sh, Carb. | 1.39 | 4.88 | **2.81** | ##### | ##### | **203.85** |
| Continuous-Type-Coal | | | | 18.97 | 33.59 | **25.44** |
| **TOTAL:** | 6.06 | #### | **10.42** | ##### | ##### | **259.82** |

*OIL + NGL

TABLE A4
ESTIMATES OF IN PLACE COAL BED METHANE
MADE BY THE TEXAS BUREAU OF ECONOMIC GEOLOGY

Compiled from Fig 1, p 8, Tyler, R. W. Kaiser, A. Scott and D. Hamilton: The potential for coalbed gas exploration and production in the Greater Green River Basin, Southwest Wyoming and Northwest Colorado: The Mountain Geologist, v 34/1 (Jan.),1997

| | **ESTIMATED IN-PLACE RESOURCE* TCF** | | | |
|---|---|---|---|---|
| **COAL BASIN** | Maximum | Minimum | Range | **Average** |
| **Raton Basin** | 8 | 12 | 8. - 12 | **10.0** |
| **San Juan Basin** | 84 | 84 | 84 | **84.0** |
| **Piceance Basin** | 84 | 84 | >84 | **84.0** |
| **Uinta Basin** | 8.3 | 10.6 | 8.3 - 10.6 | **9.5** |
| **Greater Green River I** | 314 | 314 | 314 | **314.0** |
| **Wind River Basin** | 2 | 2 | 2 | **2.0** |
| **Powder River Basin** | 30 | 30 | 30 | **30.0** |
| **TOTALS:** | 530.3 | 536.6 | 530.3 - 536.6 | **533.5** |

*NOTE: This is total "in place" resource. Volumes in coals > 4000 ft depth may not be producible at the present state of technology due to the absence of open cleats that provide permeability.

## TABLE A5
## ESTIMATED ROCKY MOUNTAIN COALBED METHANE RESOURCES
### Gas Research Institute (GRI), 1999, North American Coalbed Methane Resource Map

| Coal Basin or Deposit | State(s) | Coal-bearing Fms or Gps | Area sq. mi | In-place Coal Billions short T | Coal Rank | Coalbed Gas, TCF | |
|---|---|---|---|---|---|---|---|
| | | | | | | In-place | Recoverable |
| San Juan | CO, NM | Fruitland<br>Menefee | 7,500 | 358 | Hvb-Lvb | 84 | 11.567 |
| Piceance<br>& Uinta | CO,<br>UT | Mesaverde<br>Blackhawk, Ferron | 6,700<br>14,450 | 289<br>65 | Hvb-An<br>Sb-Hvb | 99<br>10 | 5.528 |
| Powder River | WY, MT | Ft. Union, Wasatch | 25,800 | 1300 | Lig-Sb | 39 | 9.329 |
| Raton | CO, NM | Raton, Vermejo | 2,200 | 52 | Hvb-Mvb | 10 | 3.493 |
| Greater Green River | WY, CO | Ft. Union, Lance, Mesaverde, Frontier | 21,000 | 287 | Sb-Hvb | 214 | 2.500 |
| Kaiparowits Plateau | UT | Straight Cliffs | 1,650 | 62 | Sb-Hvb | 10 | -- |
| Wind River | WY | Ft. Union, Mesaverde | 8,100 | 87 | Lig-Hvb | 6 | 2.450 |
| Bighorn | WY, MT | Ft. Union, Mesaverde | | 28 | Lig-Hvb | 3 | 0.825 |
| Denver | CO, WY | Denver, Laramie | | 51.8 | Lig-Sb | 2 | 0.300 |
| Henry Mtns. | UT | Ferron | | 1.1 | Sb-Hvb | -- | 2.745 |
| Black Mesa | AZ | Dakota, Mesaverde | 3,200 | 21 | Sb-Hvb | -- | 0.180 |
| | | | | | TOTALS: | 477 | 38.917 |

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