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CREATION OF DIGITAL DATABASES AND DERIVATIVE PRODUCTS FOR COAL AND COALBED METHANE RESOURCE ASSESSMENT: A SHORT COURSE

R.M. Flores
U.S. Geological Survey
Denver, Colorado 80225

U.S Geological Survey
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OVERVIEW

Coal makes up a vast resource in the United States and many other countries. In addition, methane associated with the coal is increasingly an emerging clean energy resource. Thus, knowledge of the size, distribution, quantity, and quality of coal deposits and related coalbed methane is important for governmental and industrial planning for short to long term energy needs of the country. In order to gain this knowledge it is necessary to create a database or an entire body of data. Data (fig. 1) is factual information such as measurements or statistics used as a basis for calculation (for example, thickness of coal and other rock types, calorific value of coal, chemical composition of the coal). This short course will attempt to demonstrate creation of databases (fig. 2) as applied to Tertiary Fort Union Formation coal and associated coalbed methane resource assessments in the northern Rocky Mountains and Great Plains region by the U.S. Geological Survey (USGS).

The goals of the coal resource assessment of the Fort Union Formation and equivalent rock units in the northern Rocky Mountains and Great Plains region were to: (1) compile the information needed to assess selected coal beds and zones of the Fort Union Formation and its equivalent formations that are potentially minable in the next few decades, (2) identify clean and compliant coal that meets standards of the Environmental Protection Agency for sulfur, ash, and trace elements of environmental concern, (3) create a publicly available digital database that can be rapidly accessed and analyzed to provide information critical to decision-making by government, industry, and the public, and (4) produce widely available digital products accessible in a variety of interpretive and interactive forms. In order to accomplish these objectives, it was necessary to create a computerized database that contained several types of data (fig. 3) including geographic (fig. 4), stratigraphic (fig. 5), and analytical (fig. 6) information. Data were stored, retrieved, manipulated, and analyzed utilizing StratiFact software (GRG Corporation, 1998). This software consists of a relational database (fig. 7) manager and a graphical interface.

Data were acquired through cooperation with the U.S. Bureau of Land Management, State geological surveys, U.S. Office of Surface Mining, and coal companies. The USGS National Coal Resources Data System (NCRDS) also provided digital data. Proprietary and non-proprietary data from these sources consist of drill-hole or outcrop measured section (fig. 8) information and coal quality and coal geochemical analyses provided to the USGS in hard copies or in digital format. The data from hard copies were entered manually into spreadsheets using spreadsheet software. The digital files were transformed into processible formats (ASCII) and downloaded into the StratiFact database manager (fig. 9). When all datasets from each drill hole were edited, correlated, and checked for quality control, the completed StratiFact database was queried to retrieve information to generate digital files for processing in other software (for example, ARC/INFO, ArcView, EarthVision) for calculation of coal resources.

DATABASE CONSTRUCTION

Data for the Fort Union Formation and equivalent units were obtained mainly from drill holes. Measured sections in outcrops were used as control points. Data from 18,207 drill holes (fig. 10) were collected from government and private industry sources for this assessment. More than seventy-five percent of the drill holes are from coal exploratory drilling. The rest are from oil and gas exploration. Thus, the basic component of the database is a drill hole bored vertically from a surface location (fig. 11). Information from the drill hole is in the form of driller's or geologist's lithology logs from rotary drill cuttings or cores, and geophysical logs (for example, gamma ray, density, neutron, resistivity, and spontaneous potential). The digital traces of the geophysical logs were not included in the database.

The geophysical logs, which make up a large part of the drill-hole information, require special analysis to measure the thickness of coal beds and related rocks (fig. 12). The precision and accuracy of measurement of thickness of coal beds and adjacent rocks on geophysical logs depend on the speed of logging, scale of the log, type of log, type of equipment, and instrument settings (Vaninetti and Thompson, 1982; Wood and others, 1983). Perhaps the most important part of the log analysis is the ability of the user to identify the top and bottom of the beds by using the points of inflection and mid-point of inflection methods (figs. 13 and 14; Wood and others, 1983, p. 55). The points of inflection method requires picking the top and bottom of the beds where the curves change directions. The mid-point inflection method requires picking the top and bottom of the beds at points midway between the points of inflection and the initial peak. Thus, the value and accuracy of the geophysical logs in measuring the thickness of coal beds and adjacent rocks varies with the experience of the users. However, because the Fort Union coal beds are very thick (figs. 13 and 14), the "operator's error" with the use of either method is considered negligible.

The basic information required for the StratiFact database manager from each drill hole includes; (1) point identification and geographic location (fig. 15), (2) stratigraphy (fig. 15), and (3) depth-based coal (analytical) data. More information on file designs or configuration of the database manager can be found in the guide to the StratiFact published by GRG Corporation (1998).

DRILL-HOLE LOCATION AND STRATIGRAPHIC DATA

The drill-hole identification is typically a unique hole number or a hole name. Drill-hole location coordinates were entered in Universal Transverse Mercator (UTM), decimal latitude and longitude, or state plane. Drill-hole elevation data were entered as part of the location table. In the stratigraphy table the rock types (for example, coal, sandstone, siltstone, mudstone, etc.) were entered along with the top and bottom depth of the lithology and lithologic name. The term "rock" was entered if the lithology between the coal was either undifferentiated sandstone, siltstone, mudstone, carbonaceous shale, and limestone or if it was unidentified. The stratigraphic data table also contains formation names (for example, Fort Union Formation), and subdivisions labeled as coal zones (for example, Wyodak-Anderson) consisting of one or more coal beds, and unassessed zones above and below the coal zone (fig. 15). The assessed and unassessed coal zones are identified according to the names of coal beds contained within the zones and members of the formation in which they exist. A drill hole may penetrate one or more stratigraphic formations or members of a formation that contain alternating coal beds and rock types. The coal beds are recognized by standard nomenclature (fig. 16) and may exist in one or more members and in a formation.

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THE CONCEPT OF A COAL ZONE

Throughout the northern Rocky Mountain region, individual coal beds commonly thicken or thin, merge or split into thinner beds separated by rock units (for example, sandstone, siltstone, and mudstone), or pinch out. Coal splits into two or more beds that gradually thin or pinch out or interfinger with clastic rocks. A "zone" consists of an interval of coal beds and interbedded rock units that contain coal in one or more beds. This "zone" is more correlatable over a wide area than are the component coal beds (fig. 17).

The term coal zone is used in this investigation to define related coal beds that are in stratigraphic proximity to each other but may not consists of laterally persistent units. Coal-zone names are either adopted from accepted nomenclature or are selected from the coal-bed names, from bottom to top of coal within the interval. Figures 18, 19, 20, 21, and 22 are diagrammatic representations of variation of coal beds in coal zones studied in the Powder River, Williston, Hanna, Carbon, and Greater Green River Basins. A coal zone in these basins typically contains from one to as many as eleven coal beds. In the Wyodak-Anderson coal zone in the Powder River Basin (fig. 23) the coal beds, from west to east, are split by fluvial deposits, merge into one thick bed, resplit, and remerge into another thick bed. Associated coal beds above and below the Wyodak-Anderson coal zone thin westward and pinch out or abut against "want areas" or fluvial channel deposits (fig. 24). Separate coal beds may exist within the coal zone at some places, but some is missing elsewhere. In addition, a coal zone in one area may be interconnected with the same coal zone in an adjoining area by either a coal bed at the top, in the middle, or at the bottom of the coal zone (see fig. 17). The laterally juxtaposed coal zone forms a series of "onlapping" or "zigzagging" patterns (fig. 25) throughout the basin of deposition. Because of very complicated stratigraphic relationship of coal beds within the coal zone, the coal resource assessment is more easily performed on the entire coal zone rather than on the individual coal beds. The continuity of the coal zone over a large area makes it more amenable for more accurate calculations of coal resources than would assessment of individual beds.

CORRELATION OF COAL BEDS AND ZONES

The coal zone is established in order to facilitate correlation of the various coal beds and associated rock types (figs. 26-28). The regional and local geologic structures and lithofacies association or depositional settings of associated rock types guide correlation of coal beds. Differences in depths of coal beds may be explained by the structural dip of rocks and by structural faults and folds (Whitacker and others, 1978; Broadhurst and Simpson, 1983; Weisenfluh and Ferm, 1984). Occurrences of coal beds near the surface may be controlled by ancestral (for example, glacial) and modern (for example, river) erosion. the environments and related processes at the time of deposition or peat accumulation of the coal beds (as peat deposits) influenced their lateral extent or continuity (Wanless, 1955; Ferm, 1970; Ferm and Staub, 1984; Flores, 1986). Highly dynamic environments such as deltas and rivers that laterally switched back and forth (avulsion process) during their existence, are prone to develop very discontinuous associated peat swamps that form coal (figs. 29-33). This process of avulsion causes complex stratigraphic relationships of resultant coal beds making the correlation of the coal very difficult unless it is aided by very closely spaced drill holes. In general, inactive areas associated with these environments, such as floodplains, interdeltas, and abandoned deposits, are prone to development of associated laterally extensive peat swamps and subsequent coal beds. This situation would result in uncomplicated correlation of coal beds requiring less closely spaced drill holes. However, in the Powder River Basin the inactive environmental areas were commonly overrun by rivers and/or deltas and the accumulation of associated peat deposits was interrupted it resulted in want areas. Once these rivers and deltas shifted elsewhere (such as topographic low areas) the area could be reoccupied by swamps and peat accumulation would resume. This complex series of processes may explain the variable continuity of Fort Union coal beds as well as their splitting and merging within relatively short distances in the Powder River Basin. When these processes are repeated contemporaneously basinwide, the result is "onlapping" and "zigzagging" of coal beds and zones. Thus, continuity of coal beds and/or zones and associated rock types is a function of their depositional environments, and the degree of reliability of correlation is determined by the spacing of drill holes that indicate the lateral variations imposed by these geological factors.

Palynology has been applied throughout the assessment region to provide a biostratigraphic ("palynostratigraphic") framework for correlation of coal beds and zones. A palynostratigraphic zonation was developed from reference sections in selected outcrops, coal mines, and cores that are correlated to subsurface drill-hole data. The Fort Union Formation and equivalent rocks were divided into six palynostratigraphic zones designated P1 (lowermost Paleocene) through P6 (uppermost Paleocene) by Nichols (1994) (fig. 34). The palynostratigraphic zonation is the basis for age determinations of individual coal beds and zones, and for correlations of coal-bearing rocks between basins in the assessment region.

COAL ANALYTICAL DATA

Each coal sample is identified by unique sample and data point location numbers. When possible, the original location number and name were retained from the drill hole where the coal sample was collected. Location coordinates were recorded in Universal Transverse Mercator, latitude and longitude, and state plane coordinate systems. The coal analytical data consist of proximate and ultimate analyses and geochemistry (figs. 35-36) for samples obtained from drill holes and mine locations. USGS guidelines for sampling to ascertain the chemical, rank, mineralogical, petrographic, and geophysical and physical properties of coal are discussed by Swanson and Thompson (1976). Proximate analysis includes the percentages of moisture, volatile matter, fixed carbon, and ash yield and reported on either an as-received moisture-free or dry, or ash-free bases. Ultimate analysis consists of the percentages of hydrogen, carbon, nitrogen, sulfur, oxygen, and ash yield and reported on either an as-received moisture-free or dry, or ash-free bases. Calorific or heat value (Btu/lb), forms of sulfur (sulfate, pyritic, and organic), and chemistry/mineralogy of the ash (for example, aluminum, calcium, manganese, potassium, silicon, and/or sodium oxides) are also included. Prescribed methods for analyses of these physical and chemical properties of the coal are discussed in American Society for Testing and Materials (1997).

The geochemical table in our StratiFact dataset includes the 12 trace elements of environmental concern that are named in the 1990 Clean Air Act Amendments (antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, selenium, and uranium). These data were entered in a spreadsheet format and each data entry includes the depth interval, which the sample was taken, and where available the name of the coal bed or zone from which the coal sample was collected. The coal quality and geochemistry data from each sample was linked to either the actual drill hole and coal bed from which the sample was taken or to the nearest drill hole and coal interval using the point identification number and the name of the coal bed/zone. This method relates the coal quality and geochemistry data to the coal stratigraphy, permitting spatial analysis and ultimately the reporting of coal resources by general categories of coal quality (for example, apparent rank, total sulfur, pounds of SO_2 per million Btu).

COAL RESOURCE EVALUATION METHODOLOGY

Recent USGS coal resource evaluation employs computer technology for delineating and isopaching coal beds and zones, isopaching overburden, and categorizing and calculating quantities of coal. The methods employed are used to determine the thickness and volume of coal, overburden thickness of rocks above the coal, and reliability categories. The computer methods used have been deemed more efficient, more readily repeatable, more detailed, and faster than the manual methods. Detailed methods for data preparation and computer calculation of coal resources for the assessed coals in the Powder River, Williston, Hanna, Carbon, and Greater Green River Basins are discussed by Ellis and others (1999a, 1999b, 1999c, 1999d, and 1999e). Coal resource evaluations in these basins consist of estimating the volumetrics of 18 coal beds or zones (Wyodak-Anderson, Rosebud, Knobloch, Harmon, Hansen, Hagel, Beulah-Zap, Ferris 23, 25, 31, 50, and 65, Hanna 77-79 and 81, Johnson- 107, and Deadman coal beds or zones). These selected Tertiary coal beds or zones, except the Knobloch and Johnson-107, are mined, and produced more than 35 percent of the total U.S. coal production in 1998. Thus, these selected coal deposits are important to development in the next few decades.

VOLUMETRICS

In order to calculate the volume for each of the 18 coal beds and zones, it was necessary to determine the thickness (in feet) and areal distribution (in acres) of the coal. The volume of coal was calculated using these parameters and was then converted from acre-ft to short tons by factoring in the density (number of short tons per acre-ft for the apparent coal rank) of the coal. The formula used for resource calculation was: short tons = area (acres) x coal thickness x coal rank density conversion factor (for example, 1,750 short tons/acre ft for lignite, 1,770 for subbituminous, 1,800 for bituminous, and 2,000 for semianthracite and anthracite) (Wood and others, 1983) (fig. 37).

As described in the section on construction of the database, coal beds existing in vertical proximity were assigned to and correlated over large areas as a coal zone. Throughout the lateral extent of the coal zone, the zone contained one or more coal beds at each drill hole location. Thus, given the number of coal beds and their continuity per coal zone, a method was devised to measure and combine the net thickness of the coal beds in the coal zone at each data point location. The net coal thickness value was calculated using a program that considered factors such as minimum coal bed thickness to be included thickness of interburden, and the definition of rock partings and splits. Rock in the coal zone from each drill hole was identified as being either a parting or a split as defined by Wood and others (1983) (fig. 38). Rock partings exist when the thickness of the rock between coal beds in the zone is less than the thickness of the underlying and overlying coal beds. Rock splits exist when the thickness of the rock between the coal beds in the zone is more than the thickness of either the underlying or overlying coal beds. These criteria are tailored to the estimation of coal resources where a coal bed bifurcates into two or more beds, as in the coal zone. This classification is required in order to accurately calculate the net coal thickness of coal within a coal zone.

COAL RESOURCE CATEGORIES

A standardized method for reporting reliability categories of coal resources has been established for the U.S. Geological Survey (USGS) by Wood and others (1983). This coal resource classification system is an expansion of the system adopted by the U.S. Geological Survey (1976) and used by Averitt (1975) in reporting 1974 U.S. coal resources. The USGS (1976) and the U.S. Bureau of Mines modified the system used by Averitt (1975), which was a standard reference for coal resource/reserve assessment used by many Federal and State agencies. Our coal resource reporting categories generally follow the 1983 USGS methodology (Wood and others, 1983).

The USGS coal resource classification system is based on geologic assurance of correlation accuracy that is directly related to the distance from drill-hole (control point) sites where the coal thickness and overburden thicknesses are measured. The specified distances from drill holes (control points) are designated by reliability circles: 0-0.25 mi (0-0.4 km) radius for measured coal, 0.25-0.75 mi (0.4- 1.2 km) radius for indicated coal, 0.75-3.0 mi (1.21-4.83 km) radius for inferred coal, and beyond the 3 mi (>4.83 km) radius for hypothetical coal (fig. 39). This classification system is designed to quantify the amounts of coal (1) that are known, or identified resources (measured, indicated, and inferred reliability categories), and (2) that remain to be identified (hypothetical reliability category). The distance reliability categories, as well as the net coal thickness category (2.5-5 ft or 0.75-1.5 m, 5-10 ft or 1.5-3 m, 10-20 ft or 3-6 m, 20-40 ft or 6-12 m, and >40 ft or >12 m) and the overburden thickness category (0-100 ft or 0-30 m, 100-200 ft or 30-60 m, 200-500 ft or 60-150 m, and 500-1,000 ft or 150-300m), are required for reporting resources (tables 1-5) for the Fort Union lignite and subbituminous coal (>500 ft or 150 m is used because no or little overburden exceeds 1,000 ft or 300 m). The amount of overburden (thickness of rocks above the coal zone) was calculated by subtracting the grid of the surface elevations from the grid of the elevation of the top of the coal zone. Coal resources reported by county, State, 7.5-minute quadrangle map area, Federal versus non-Federal surface (tables 3-4) and coal ownership, coal quality (using ash yield and sulfur content, and pounds of SO_2/million Btu), and apparent coal rank (as indicated by moist, mineral-matter free Btu; American Society for Testing and Materials, 1997) categories. The coal resources reported on tables 1-5 do not include mined out and leased areas, areas containing burned coal and associated rocks (clinker) and coal resources in Indian tribal lands.

COMPUTERIZED METHODS

Several computer software programs were used to create digital information for the calculation of the coal resources. ARC/INFO software was used to create layers of spatial digital information or coverages (for example, state boundaries, counties, geological boundaries, mine and lease boundaries, quadrangle maps, clinker, reliability areas, point locations, etc.). These coverages are in Lambert Conformal Conic projection, Clarke Spheroid 1866, with parameters of first standard parallel of 33°, second standard parallel of 45°, and central meridian of -106°.

The computer method for calculating coal resources involved compensating for the irregular distribution (x and y values) of drill-hole data (dense versus sparse distribution) within the study basins. In order to compensate for this distribution, a rectangular grid was superimposed over the data area and a Z value (net coal thickness) was interpolated by computer and extrapolated from the existing data. This gridding procedure was performed using the EarthVision software. Different grid sizes and algorithms were tested to determine the appropriate grid to generate isopach maps. Resource calculations were dependent on these calculated nodes and sub-nodes (Ellis and others, 1999a; Roberts, 1998). Coal thickness isopach and overburden maps produced in EarthVision were imported into ARC/INFO software and were combined with other spatial layers to produce unioned coverages. These union coverages consist of spatial information such as counties, State, 7.5-minute quadrangle map area, and Federal versus nonfederal ownerships of coal the land surface. After unioning all the coverages, the resulting coverage was clipped to the coal zone areal extent. The ARC/INFO union coverage polygon files were imported into EarthVision and used to calculate the volume of coal in each polygon. This method, which uses the net coal thickness grid node and sub-grid node values of the coal thickness, was determined to be the most accurate method for estimating coal resources by computer (Ellis and others, 1999a, Roberts, 1998).

The coal resources were reported in tables, which contain information on overburden, coal thickness, and distance reliability categories. Coal resources within each of these categories are reported in million short tons with two significant figures. Schuenemeyer and Power (1998) developed a procedure for the estimation of confidence limits, which represent uncertainty or measurement of error on the volume of coal resources as a part of the USGS National Coal Resource Assessment (table 5).

APPLICATIONS OF COAL RESOURCE ASSESSMENT TO COALBED METHANE EXPLORATION AND DEVELOPMENT: METHODS AND PROCEDURES

The recently completed USGS coal resource assessment of the Fort Union coal beds and zones in the northern Rocky Mountains and Great Plains region (Fort Union Coal Assessment Team, 1999) contains useful information that can be applied to coalbed methane exploration and development in the Powder River Basin, Wyoming and Montana. Methane development from the subbituminous Fort Union Formation coal started with two wells that produced more than 200,000 mcf (thousands of cubic feet) in 1981. These wells were shallow, varying from about 550 to 700-ft (165-210 m) in total depth. It is projected that more than 35,000 producing wells will be completed in a decade. The rapid rate of development in the Powder River Basin is driven by the low cost of drilling shallow wells (mainly less than 2,000 ft below the surface), which can be completed in a few days. There are currently more than 11,000 coalbed methane wells that are permitted to drill in the Powder River Basin (fig. 40). Total cumulative production from January to December, 1999 was more than 57 billion cubic feet and from approximately 1,200 wells (figs. 41 and 42).

It has long been known that the low rank Fort Union coals in the Powder River Basin contain some methane. A number of flowing artesian water wells at shallow depths (245 to 415 ft or 73.5-124.5 m) investigated by the USGS (Olive, 1957; Lowry and Cummings, 1966; and Whitcomb and others, 1966) contained substantial amounts of methane. USGS investigators (Hobbs, 1978; Boreck and Weaver, 1984) reported the gas content and chemical analysis of the methane in the Fort Union coal. Hobbs (1978) measured the methane content (8-9 standard cubic feet per ton or scf/t) in 15 shallow drill holes (400-500 ft or 120-150 m below the surface) in the Recluse area of northeastern Campbell County and in an area south of Gillette, Wyoming. Those drill holes penetrated the Wyodak-Anderson coal zone area, which includes the Anderson and Canyon coal beds in the Recluse area. Methane has been encountered in the coal beds as well as in overlying sandstone beds and interbedded siltstone and shale beds. Gas flow rates have been reported as varying from a trace in shale interbeds to more than 1,000,000 cubic ft/day. Hobbs (1978) suggested that potential methane production could occur from the Anderson and Canyon coal beds, from fluvial channel sandstones between the coal beds, and possibly from below the Canyon coal bed.

Coalbed methane exploration and development in the Powder River Basin has rapidly accelerated since the mid 1990's. More than 11,000 wells have been drilled since 1981 but only 35 coalbed methane wells were drilled and completed from 1981 to 1990. This number gradually increased to 229 from 1990 to 1995 and began to increase greatly by about 1996. By early 1999 coalbed methane wells were being completed at a rate of more than 50 per month, so that by December 1999 more than 1,500 wells were producing in the Wyoming part of the Powder River Basin and more than 70 wells were producing in Montana. The number of producing wells will continue to increase as the shut-in wells become connected to the pipeline network. This rapid pace of development is expected to continue. Development of shallow (less than 1,500 ft deep or 450 m) Fort Union coalbed methane is confined to Campbell and Sheridan Counties Wyoming, and Big Horn County, Wyoming. Development of deep (more than 1,500 ft or 450 m deep) Fort Union coalbed methane is confined to Johnson County, Wyoming. There, the targeted coal beds are mainly the Anderson and Canyon of the Wyodak-Anderson coal zone sometimes called the Big George, Anderson-Canyon, or Wyodak coal zones (see figs. 23 and 25). However, as many as 20 other coal beds are also targeted for development. The following section of the short course discusses the methodologies and procedures that the USGS utilizes to analyze, evaluate, and assess coalbed methane in the Powder River Basin in Wyoming and Montana.

COALBED METHANE PLAY IN THE FORT UNION FORMATION IN THE POWDER RIVER BASIN

Perhaps the most promising coalbed methane play in the Powder River Basin is found in the Wyodak-Anderson coal zone in the upper part of the Fort Union Formation. The top of the coal zone generally ranges from 300 to 2,500 ft (90 to 750 m) deep. The coal zone is as much as 550 ft (165 m) thick containing individual beds (as many as 11) as thick as 202 ft or 69.6 m (Boreck and Weaver, 1984; Hardie and Van Gosen, 1986). The isopach map of the Wyodak-Anderson coal zone exhibits a series of discontinuous, ovoid (8 to 22 sq. mi) coal bodies that are from 150 ft (45 m) to more than 200 ft (60 m) in net coal thickness. These ovoid coal bodies are surrounded by elongate deposits of more than 1,000 sq.-mi that range from 100 to 150 ft (30 to 45 m) in net coal thickness. These ovoid and elongate coal deposits are generally oriented in a north-south direction and contain resources of about 194 billion short tons (Fort Union Coal Assessment Team, 1999). A regional cross section through the northern half of the area shows split and merged beds of the Big George coal zone, which reaches as much as 202 ft (60.6 m) thick in that area. To the south, the Big George coal zone splits into many thinner beds, several of which merge with the Sussex coal zone, which attains a thickness of up to 138 ft (41.4 m). Where the coal beds split and merge, they are interbedded, overlain, and underlain by fluvial channel sandstones. These sandstones may contain recoverable methane (dry gas) that has migrated from the coal reservoir.

Other coal deposits, above and below the Wyodak-Anderson coal zone in the Fort Union Formation are also promising targets for methane development. Examples of these coal beds are the Wall coal, as much as 25 ft (7.5 m) thick; Pawnee coal, as much as 60 ft (18 m) thick; Gates coal as much as 25 ft (7.5 m) thick; Knobloch coal, as much as 70 ft (21 m) thick; Rosebud coal, as much as 25 ft (7.5 m) thick; and Broadus coal as much as 30 ft (19 m) thick. In the Wasatch Formation, which is above the Fort Union Formation, the Felix coal bed, as much as 40 ft (12 m) thick and Lake deSmet coal bed as much as 250 ft (75 m) thick are also promising targets for methane development.

GAS CONTENT OF THE FORT UNION COALS IN THE POWDER RIVER BASIN

Gas desorption of seven samples from the Wyodak-Anderson or Big George coal bed at B23-BG1CB test well drilled in 1983 by the USGS in Johnson County, Wyoming yielded from 56 to 74 standard cubic feet per ton (scf/t) (at standard conditions are 60° Fahrenheit and at atmospheric pressure of 14.7 pounds per square inch or psi) and an average of 64 scf/t gas content (Boreck and Weaver, 1984; table 6). This is in contrast to analyses of three core samples from Fort Union coal in the Betop Incorporated Dead

Horse Creek 8-32 well drilled in 1989 in Campbell County, Wyoming that indicated a gas content from 26 to 44 scf/t and an average of 30 scf/t (table 7). Additional gas desorption of 22 core and cutting samples of the Wyodak coal in the Exxon # 2 Robert C. Harper "B," #1 Shotgun Federal, and #2 Shogrin Federal wells drilled in 1992 (table 2) yielded gas contents varying from about 6 to 44 scf/t and an average of about 26 scf/t (measured from coal core and cutting samples). These old gas content estimates are unreliable because they are based on different types of samples and did not consider canister head space, temperature of the coal in the canister, desorption measurements at reservoir temperature, and measurements of coal densities. The old procedures may have underestimated the gas contents of Fort Union coal. New estimates of gas content of the Canyon coal of the Fort Union Formation, which considered these parameters, yielded an average of 21.2 scf/t (Mavor and others, 1999). Even if errors in gas content measurements obtained during the early development projects are discounted, the apparent in-situ gas content of the coal is low in comparison to other producing basins.

The old (table 7) and new gas content (Mavor and others, 1999) estimates are difficult to compare; however, a few general trends may be interpreted regarding the Fort Union coalbed methane play in the Powder River Basin. (1) The Fort Union coal in the central and deepest part of the basin represented by the coal cored in the USGS "Big George" well contains a relatively high gas content. (2) The Fort Union coal found between the deepest and shallowest parts of the basin represented by the coal cored in the Betop and Exxon wells contain a relatively low gas content. (3) The Fort Union coal found along the eastern margin and shallowest part of the basin represented by the coal cored in the Redstone well contains the lowest gas content. Applying the 21.2 scf/t (minimum) and 64 scf/t (maximum) average gas contents to the coal resource calculation of 550 billion short tons for the Wyodak-Anderson coal zone (Ellis and others, 1999b) allows one to estimate a range methane-in-place in the basin. The minimum gas-in-place for the Wyodak-Anderson coal is about 11 trillion cubic feet (tcf) and the maximum gas-in-place resource is about 35 tcf. In comparison, Rice and Finn (1996) calculated the gas- in-place resource as 30 tcf using an average gas content of 25 scf/t for all coals in the Powder River Basin.

Gas content of Fort Union coals may be influenced by the nature of the porosity and composition as reported by Bustin (1999a, b). According to Bustin (1999b) free gas stored in the matrix and fracture porosity (meso and macroporosity) in low rank coal of the Fort Union Formation may contain up to 50 percent of total produceable methane depending on moisture content of the coal.

BIOGENIC ORIGIN OF FORT UNION COALBED METHANE

Boreck and Weaver (1984) reported the chemical composition of the gas in the Wyodak-Anderson coal from the USGS "Big George" test drill hole in Johnson County, Wyoming (table 8). These workers suggested a biogenic origin of the methane, confirmed by Rice and Flores (1990, 1991) and Rice (1993), which reported the Wyodak-Anderson coal to be enriched in the light isotope ^{12}C (with methane $\delta\,^{13}C$ values ranging from –56.5 to –53.8 parts per thousand; fig. 43). Rice (1993) discussed the importance of bacterial activity in generating methane in the low rank Fort Union coal beds.

Biogenic gas in the coal, which is composed mainly of methane and carbon dioxide, is produced by decomposition, by bacteria or microbes, of the organic matter in peat deposits. During this process of organic matter breakdown (methanogenesis), a diverse population of microbes contributed to partial oxidation of the organic matter (Rice, 1993). Methanogenic bacteria only operate during the final stages of decomposition and depend on other microorganisms to convert complex compounds into simple precursors (Rice and Claypool, 1981). Biogenic gas in the low rank Fort Union coal in the Powder River Basin was formed during the early and late coalification stages. The gas accumulated in association with the introduction of groundwater systems during the late burial of the rocks providing a favorable environment for bacterial activity for late stage biogenic gas generation (Rice, 1993).

Although methane recovered from coal core samples in the Powder River Basin indicated biogenic origin, there is presently a debate on what percent of the methane is "early stage" biogenic gas, formed shortly after peat accumulation, and what percentage is "late stage" biogenic gas, formed after uplift, erosion, and the development of thick coal beds as major aquifers in the basin (Rice, 1993). The introduction of groundwater systems would have increased microbial activity within the coal resulting in "late stage" methane production. Rice (1993) suggests that much of the "early stage" biogenic methane may have escaped prior to or during regional uplift and erosion which began about 10 million years before present. If so, the relatively recent introduction of groundwater systems into the coal beds in the Powder River Basin was the key to the development of the Fort Union coalbed methane resource.

OLD AND NEW PROCEDURES FOR EXPLORATION AND DEVELOPMENT IN THE POWDER RIVER BASIN

Although methane was known to occur in Fort Union coals for many years, exploration did not begin until late 1980's. Early models onfcoalbed methane (CBM) development in high rank (bituminous) coals of the Black Warrior Basin in Alabama and San Juan Basin in New Mexico utilized conventional well completions (for example, cementing and casing across the entire coal bed followed by perforating and acidizing) and conventional spacing pattern procedures. These same drilling practices were originally applied to develop CBM from the low rank Fort Union coal as well. The relatively low gas content of the subbituminous Fort Union coal and abundant co-produced water were not conducive to these original procedures. Applying the older procedures led to uneconomic production and early abandonment of coalbed methane projects in the Powder River Basin. Only very marginal production of coalbed methane was attained, therefore, CBM development was believed to lack economic potential in the basin.

Economic production of the coalbed methane in the PRBwas achieved only in the mid 1990's when drilling and well completion procedures were revised by setting well casing to the top of the coal, cementing the casing, and then under reaming the coal to a larger diameter than the drilled hole, thus exposing more surface area for gas desorption. Improved well completion procedures played a major role in allowing economic coalbed methane production in the Powder River Basin (McGarry, 2000). The conventional completion procedure of casing and perforating the coal beds did not promote effective gas desorption and acid treatments damaged the coal and inhibited recovery. Another factor that contributed to economic production of methane in the low rank coal was the introduction of an efficient method to dewater the coal beds. Early coalbed bed methane wells were drilled on 160-acre or larger spacing patterns, which was an inefficient method of dewatering the coal. Presently, 40- or 80-acre spacing patterns promote maximum efficiency of dewatering procedures.

An improved technique for dewatering was vital to initiate productive recovery of the methane. Dewatering of the coal is currently being accomplished in the Powder River Basin by drilling and producing wells in-groups or "pods." A "pod" is a gas-gathering station that serves from 10 to 22 wells. Dewatering and gas desorption are also enhanced by development of initial wells in small structural highs. As dewatering continues structural relief becomes less important and production is accelerated in lower structural areas.

PROCEDURAL ERRORS IN COLLECTING METHANE DATA IN THE POWDER RIVER BASIN

The major reason for the failure in the early efforts to develop coalbed methane in the Powder River Basin is the inadequate procedures that were used to test and measure gas content. Applying inappropriate procedures for degassing the low rank coals found in the Powder River Basin exacerbated this failure. The original procedure resulted in incorrect measurements of gas contents, which in turn caused the underestimation of coalbed methane resources and led to incorrect or uneconomic projections for the gas-in-place reserve of the basin. The accepted method of measuring gas content in the coal beds is by desorbing gas from core samples. The early measurements of the gas content based on drill cuttings resulted in errors of about –25 percent (Mavor and Nelson, 1997). Additional errors in estimating methane content can result in the common practice of collecting and measuring only a few selected cores from the entire coal bed. Measurement errors were also caused by not conducting gas desorption at reservoir temperature in water baths, which resulted in errors of about –30 percent in total gas calculations and –60 to –70 percent in lost gas calculations (Mavor and Nelson, 1997). Furthermore, the use of incorrect coal densities caused errors of –10 to –13 percent.

Available information on measurements of methane content of the Fort Union coal in the Powder River Basin indicate that some gas desorptions were from drill hole cuttings rather than coal cores. A large majority of the measurements were performed at ambient (room) temperature rather than at reservoir (water baths) temperature. Many operators used only selected core samples for gas desorption because of costs associated with coring and desorbing a continuous core from the entire coal bed. Although density logs were collected, they were not used as a factor to consider when calculating gas content.

In order to obtain correct measurements of gas content of the Fort Union coals in the Powder River Basin, the USGS devised new procedures and methodologies that were modified from the latest published techniques. To develop a new technique for measuring gas content of high rank coals the USGS modified accepted techniques developed by the former U.S. Bureau of Mines and the Gas Research Institute. Those techniques were specially adapted to fit the low rank coals in the Powder River Basin. These new USGS procedures are discussed in the following section.

USGS COALBED METHANE DATA COLLECTION PROCEDURES IN THE POWDER RIVER BASIN

Presently the USGS is investigating the methane play in the Powder River Basin in partnerships with the U.S. Bureau of Land Management (BLM) and numerous gas operators. The objectives of this study are:

1) To make a reliable gas in-place database for coal beds in the basin. Focus will be on areas where the most extensive and highest quality data can be obtained and where gas operators provide continuous coal cores for testing. Existing data from the USGS National Coal Resource Assessment, BLM and State files, and proprietary sources will be combined with new data obtained from cooperating gas operators to best estimate gas in place for various parts of the basin. The data will be used to estimate gas reserves in remaining areas on the basis of comparable models from the analyzed parts of the basin. Final analysis will include a geology- and engineering-based assessment of potential additions to reserves of gas. Potential additions to the reserve are those resources in known or undiscovered accumulations that can be postulated to become proved reserve in a 30-year time frame.

2) To develop better methodologies for determining gas in place of thick sequences of coal. Methodologies will utilize and develop techniques for capturing gas in a comprehensive manner to best represent the variability in the coal; geophysical logging techniques to infer and document compositional changes in the coal strata; chemical analysis of coal and captured gas; petrographic and biofacies analysis of the coal; and determination of variability of fractures and cleat formation.
3) To develop models to explain the origin, variability, and distribution of biogenic gas in low rank coal beds. Depositional modeling will be used to establish the geometry of the coal beds. Hypotheses will be tested on the origin of the biogenic methane degassed from the coal. Specifically, the gas could have been produced early in the coalification process, or the gas may have been generated fairly recently after uplift and erosion exposed the coal to groundwater systems. The effects of coal lithotypes, regional groundwater circulation, or compactional fractures, and development and distribution of cleat on gas production and entrapment will be investigated.
4) Analyze the chemical and isotopic composition of co-produced waters and to develop hydrology models to determine variations of waters produced from the coalbed methane wells, potential leakage from adjacent aquifers, mixing of water types, water sources and recharge, and evolution of water chemistry.

METHODOLOGY FOR DESORBING GAS

To populate a reliable coalbed methane dataset for this study we had to develop a reliable method for obtaining accurate measurements of desorbed gas from drill core samples. This methodology consists of the following procedures. Continuous coal cores are collected (depending on core recovery) from the entire coal bed drilled. Gas desorption of the coal utilize canisters that are 28-inch (61.12 cm) long with 4.5-inch (11.43 cm) outside diameter and 4-inch (10.16 cm) inside diameter. The canisters are constructed of PVC pipe with a permanently sealed top cap with valve and temperature-well assemblies and removable mechanical bottom gripper plug (fig. 44). USGS personnel, utilizing and modifying the National Occupational Safety and Health (formerly U.S. Bureau of Mines) canister design constructed the canisters. About 300 canisters were constructed. The canisters were designed to facilitate multiple and overlapping desorption jobs for a wide range of coal-sample sizes.

The methodology for desorbing gas from continuous coal cores, analyzing coal gas, and determining coalbed methane content utilized by the USGS are as follows:

1) Record weight of empty canister.
2) Measure reservoir temperature from co-produced water of identical coal beds in nearby wells.
3) Record time when top of coal sample was cored.
4) Record time when core barrel started out of the well.
5) Record time when the core barrel arrived on the surface.
6) Record original depth interval of cored coal (bottom and top).
7) Divide the coal core in a run (length varying with the length of the core barrel and effectiveness of core recovery) into 2-ft or 60.96 cm (section) samples.
8) Place coal samples into canisters marking the footage on the top and bottom of the coal sample.
9) Seal the canisters; record the date, time, ambient temperature, and barometric pressure; and record the temperature of gas and coal inside the canister. Place the canisters in water baths or tanks (30-in-diameter x 36-in.-deep or 60.96 x 81.44 cm plastic tanks designed by USGS personnel) and maintain the water in the tank at reservoir temperature through the use of an immersion circulation heater.
10) For the first nine hours (minimum recommended in the literature) after canisters are sealed, the desorbed gas is measured by the amount of displaced water in a graduate cylinder. Desorbed gas is measured and recorded at fifteen-minute intervals. After nine hours, the increment time between readings is increased to a half-hour. When gas desorption decreases to less than 50 cubic centimeters per reading, the increment time between readings is increased to one hour. Following this procedure, the increment time between readings is increased to three hours and then to 24 hours. When a gas desorption measurement is taken, the ambient (outside the canisters) temperature, coal/gas (inside the canisters) temperature and barometric pressure are also recorded. Date and time are also recorded.

11) Canisters are then moved to a coal laboratory on the Denver Federal Center, Denver, Colorado where desorbed gas, ambient and coal/gas (inside the canisters) temperatures, barometric pressure, date and time are recorded at increasingly longer increments of time. For these readings the canisters are no longer maintained in water baths.

12) Desorbed gas is periodically collected in sealed glass containers containing a bacteria-inhibiting solution (zephiron chloride). Sampling of gas desorbed from the coal takes place when sufficient volume of gas is present. The captured gas is analyzed in a USGS geochemistry laboratory in Denver for carbon isotopic composition and chemical composition (methane, nitrogen, carbon dioxide, oxygen, argon, ethane, propane, butane, and pentane).

13) Desorbed gas is measured and recorded from the canisters until volume of gas is less than 10 cubic centimeters per day for one week.

14) At the end of the desorption process the coal-filled canisters are weighed (this weight minus the empty canister weight equals the weight of the coal). After the coal is removed from the canister, the canister is completely filled with distilled water and weighed (this weight minus the weight of the coal-filled canister equals the head space volume). Coal density is determined from these parameters minus canister volume for use in log analysis.

15) Coal that was removed from canisters is double sealed in PVC tubing and plastic bags, and the air is removed from the bags to retain moisture and minimized oxidation of the coal.

16) Coal core is sent to the USGS coal petrography laboratory in Reston, Virginia (see procedure below). The petrographer determines and describes the lithotypes, sedimentary structures, cleats, and micro- and macro-maceral compositions of the coal cores. Digital photographs and x-ray photos are taken of the continuous coal cores for additional macroscopic analysis and archiving.

17) One-kilogram-coal grab samples are collected from the cores (preferably direct from the core barrel after a core run) for adsorption analyses and density measurements. Samples are double bagged and sealed to retain moisture and to reduce oxidation and desiccation (it is recommended to heat seal and bag the

sample in water in order to keep moisture in). Samples are then sent to the RMB Earth Science Consultants Ltd., Richmond, British Columbia, Canada for analysis. These analyses produce langmuir isotherm curves, which indicate gas content (scf/t) held in the coal at different pressures (psi) on as-received, ash-free, and moisture-free bases.

18) The remaining coal samples are resealed and sent to a commercial testing laboratory for proximate and ultimate analyses. Selected samples will also have equilibrium moisture, density, free swelling index, volatile matter, and calorific values determined. Samples are split by the laboratory for use in additional petrographic (including vitrinite reflectance and inorganic mineralogy/geochemistry) and biofacies (palynology) analyses by USGS researchers in Denver and Reston.

19) All desorption data (date, time, ambient and canister temperatures, barometric pressure, and desorbed volume of gas) along with drill hole identification number, and depth of coal sampled are entered into a spreadsheet and imported into the relational database.

20) The spreadsheet data are transferred into a gas-in-place analysis program written by the Gas Research Institute, Chicago, Illinois, and Mavor and Nelson (1997) that was modified by USGS personnel. This program determines lost gas, total desorbed gas, and estimates residual gas. The total gas is reported at standard cubic feet per short ton (scf/t).

21) Additional geochemical data are gathered from co-produced water collected from producing methane wells. Analyses performed at the USGS laboratory in Denver include chemical (major, minor, and trace cations and anions) and stable isotopic (deuterium, oxygen, and carbon) compositions. These analyses help determine the origin and chemical evolution of the co-produced water of the coalbed methane. Analytical data is added to the database.

COAL PETROGRAPHY IN RELATION TO THE GENERATION OF COALBED METHANE IN THE POWDER RIVER BASIN

The purpose of including petrographic data in the database is to identify and correlate facies or subunits of the coal beds that affect the amount of coalbed methane produced, trapped, and migrated. An additional goal is to develop techniques to estimate gas-in-place using relationships correlated among measured canister gas content, megascopic descriptions of core, petrographic composition, and chemistry the low rank coals.

Continuous coal cores are described in the laboratory to facilitate the division of the coal subunits or facies. Seven major lithologic types of the subbituminous Fort Union coals have been described in cores: a) hard, woody textured, b) woody textured, c) finely laminated, d) coarsely laminated, e) very coarsely laminated, f) attritus-rich, and g) clay or impure coal.

Lamellae can consist of: a) stem and predominantly root tissues that are well preserved, b) attritus which to the unaided eye appears as granular coal, and c) less commonly, fusain or charred wood resulting from forest fires in the peat. The major differentiation among types a-c is the thickness of the woody lamellae or vitrain. In cases where vitrain is not separated by layers of attritus, these sections are described as woody textured. Two types of woody textured layers have been observed, soft and hard, possibly the result of differing types of plants or plant parts (stem versus root).

Geophysical logs are used in addition to the petrography to describe, identify, and relate possible megascopic characteristics of the low rank coal. Thus far, only fusain layers have been identified on geophysical logs. Fusain may be important to document as widespread occurrences within a particular facies and may provide a permeable layer through which gas could migrate laterally. Geophysical logs will be further studied in attempt to identify dispersed volcanic ash layers, which may play a role in sealing a layer in the peat stage and compartmentalized the resulting coal; thus the ashy layer forms a trapping mechanism for the methane.

Thin section samples of the coal will be analyzed for 22 maceral varieties. Certain macerals may indicate higher levels of biogenic activity, which would have produced increased amounts of gas. These gas-prone macerals may comprise a facies that can be megascopically identified and hence provide a model for determining gas-prone zones of a coal body.

In addition, thermal maturity using vitrinite reflectance will be determined to document basinwide coalification patterns. Rank changes in the Powder River Basin are subtle and not well documented because of the overall low rank nature of the coal. At present it is not clear whether rank plays any role in concentrating gas or moving gas in and out of the coal bodies. Finally, coal descriptions also include approximations of cleat spacing, which aid in gas migration.

COALBED METHANE DATABASE CALCULATION

The data obtained from gas desorption of the coal, coal quality, and coal petrography are utilized to estimate the gas-in-place or GIP as measured by the following equation (Mavor and Nelson, 1997).

$$GIP = 1359.7AhDG$$

Where:

GIP= gas-in-place volume in scf

A= coal (reservoir) area in acres

h= coal (reservoir) thickness in feet

D= average in-situ rock (coal) density at the average in-situ rock composition in g/cm^3

G= average gas content at the average in-situ rock (coal) composition in scf/t

Gas content estimates are not accurate without consideration of the ash yield and moisture content of the coal reservoir (Mavor and Nelson, 1997). These data are obtained from the proximate analysis of the coal (see above). The rock or coal density can be related to the density of the ash, moisture, and organic fractions. Also, the density may be estimated from open-hole density log, core or coal density, and petrographic (x-radiograph) data.

Thus, the above equation makes the gas-in-place estimates from a simple equation with parameters including the drainage area, thickness, density, and gas content (from desorption) of a coal reservoir. The gas content is defined as in-situ gas volume per unit weight of rock. The unit weight of the rock contains both organic (coal macerals) and inorganic (ash and moisture) components within the coal. Mavor and Nelson (1997) provided the spreadsheet (tables 9-11) and computer programs (figs. 45-47) for calculation of the gas-in-place volume.

SUMMARY

After drill hole and outcrop data are obtained and entered into a database, the process of evaluating coal resources involves retrieving drill-hole data from the StratiFact database manager for each identified and correlated coal zone. The data are used to create grids of measured values and finally to calculate coal tonnages (in millions of short tons) categorized according to specific intervals of depths or overburden, net thickness of coal, and degree of assurance of existence of the coal (relation of distribution and quantity of drill holes). Additional reporting categories include coal resources by counties, state, surface and subsurface ownerships, coal quality, and apparent coal rank. Coal tonnages are reported in Excel tables.

The data obtained from evaluating coal resources are used to estimate the gas-in-place (GIP) for coalbed methane resource. The most important data for calculating the GIP is the gas content measured from desorbing gas from coal cores sealed in canisters. In addition, information on the areal coverage, thickness, and density of the coal is also used in the GIP calculation.

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Table 2. Coal resource calculations by reliability categories as determined from overburden thickness (200-500 ft or 60-150 m) and coal thickness (10-200, 5-200 ft or 3-60, 1.5-60 m). Adapted from Fort Union Coal Assessment Team (1999).

Table 3. Coal resources reported by county and 7.5-minute quadrangle map. Modified from Fort Union Coal Assessment Team (1999).

Table 4. Coal resources reported by county and Federal ownership. Adapted from Fort Union Coal Assessment Team (1999).

Table 5. Coal resources reported by reliability categories as calculated by statistical and uncertainty parameters. Adapted from Fort Union Coal Assessment Team (1999).

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Table 8. Chemical composition of the coalbed methane from the Big George coal. Adapted from Boreck and Weaver (1984).

Table 9. Example of core desorption data sheet. Adapted from Mavor and Nelson (1997).

Table 10. Desorption core data sheet. Adapted from Mavor and Nelson (1997).

Table 11. Desorption core data sheet. Adapted from Mavor and Nelson (1997).

Data

- **Factual information such as measurements or statistics used as a basis for calculation**

Figure 1

Database

- Entire body of data
- Data may be spread out in two or more files called "Tables"

Figure 2

USGS
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Types of Data

1. Geographic
2. Stratigraphic
3. Analytic (coal geochemistry and quality)

Figure 3

USGS
science for a changing world

Geographic Location Table Contains:

1. Drill hole (or measured section) name
2. Coordinates
3. Elevation
4. Other spatial data (state, county, ownership, map area)

Figure 4

Stratigraphic Table Contains:

1. From / To depths
2. Lithology
3. Stratigraphic zones and sub-zones

Figure 5

Analytical Table Contains:

1. From / To depths
2. Coal geochemistry and quality data
3. Detection limits
4. Other analytical data

Figure 6

Relational Databases

- Consist of related data stored in multiple files.
- For example, our relational database is specifically designed to store drill hole/measured section data and geographic data.
- When accessing the data for a specific drill hole the software first opens the location table and then any other necessary tables.

Figure 7

USGS
science for a changing world

Data Point Id: RMF-1A
Quad & Series: Sheridan (1°)
Country: United States
State: Wyoming
County: Sheridan
Province: N. Great Plains
Region: Powder River

Geologist: Flores, R.M.
Source: Field Measurement
Surface Elevation: 4240.00'
Total Depth Logged: 13.17'
Description Log: Outcrop

Agency: USGS
Date: 1985 05 30
Rank: Subbituminous
Local Strike:
Local Dip:
Lattitude: 44° 46' 28.343"N
Longitude: 106° 15' 57.759"W
Quarters: NE NE
Section: 5
Township: 55 N
Range: 78 W

Unit	Formation	Bed Name	Lithology	Lithology Modifies	Color/Bedding Fossils	Thickness	From - Depth	To - Depth
1	Fort Union		Sdst		gy / xb / nf	20.00'	0.00'	20.00'
2	Fort Union		Mdst		dgy / ms / pf	4.00'	20.00'	24.00'
3	Fort Union	Anderson	Coal	Banded		25.00'	24.00'	49.00'
4	Fort Union		Sh	Rooted	dk / ms / pf	1.00'	49.00'	50.00'

Figure 8

DATABASE MANAGER MAIN DATA FLOW
Going From Data To Reports

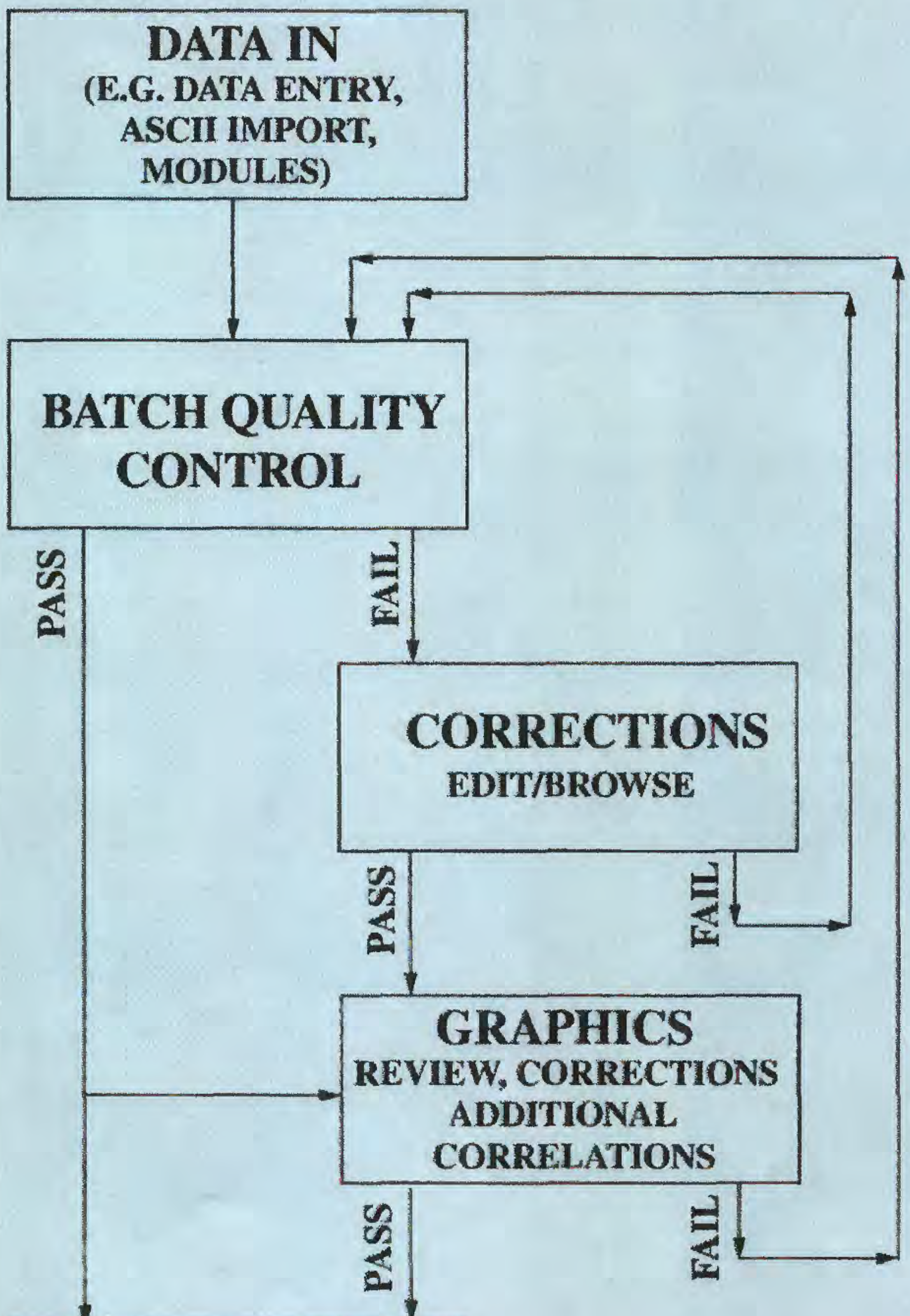


Figure 9

USGS
science for a changing world

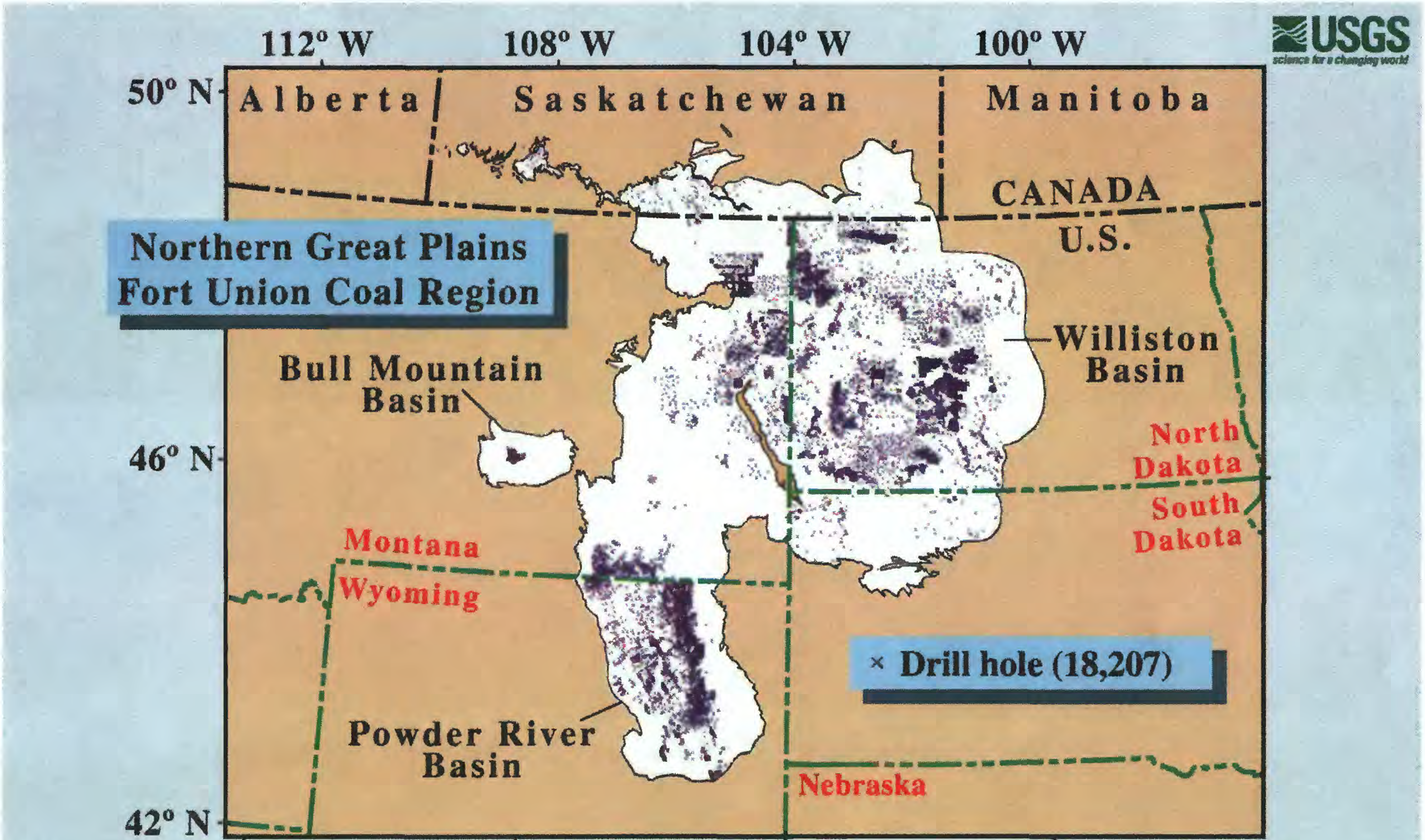

Northern Great Plains
Fort Union Coal Region
112° W
108° W
104° W
100° W
50° N
46° N
42° N
Alberta
Saskatchewan
Manitoba
CANADA
U.S.
Bull Mountain Basin
Williston Basin
North Dakota
South Dakota
Montana
Wyoming
Powder River Basin
Nebraska
× Drill hole (18,207)

Figure 10

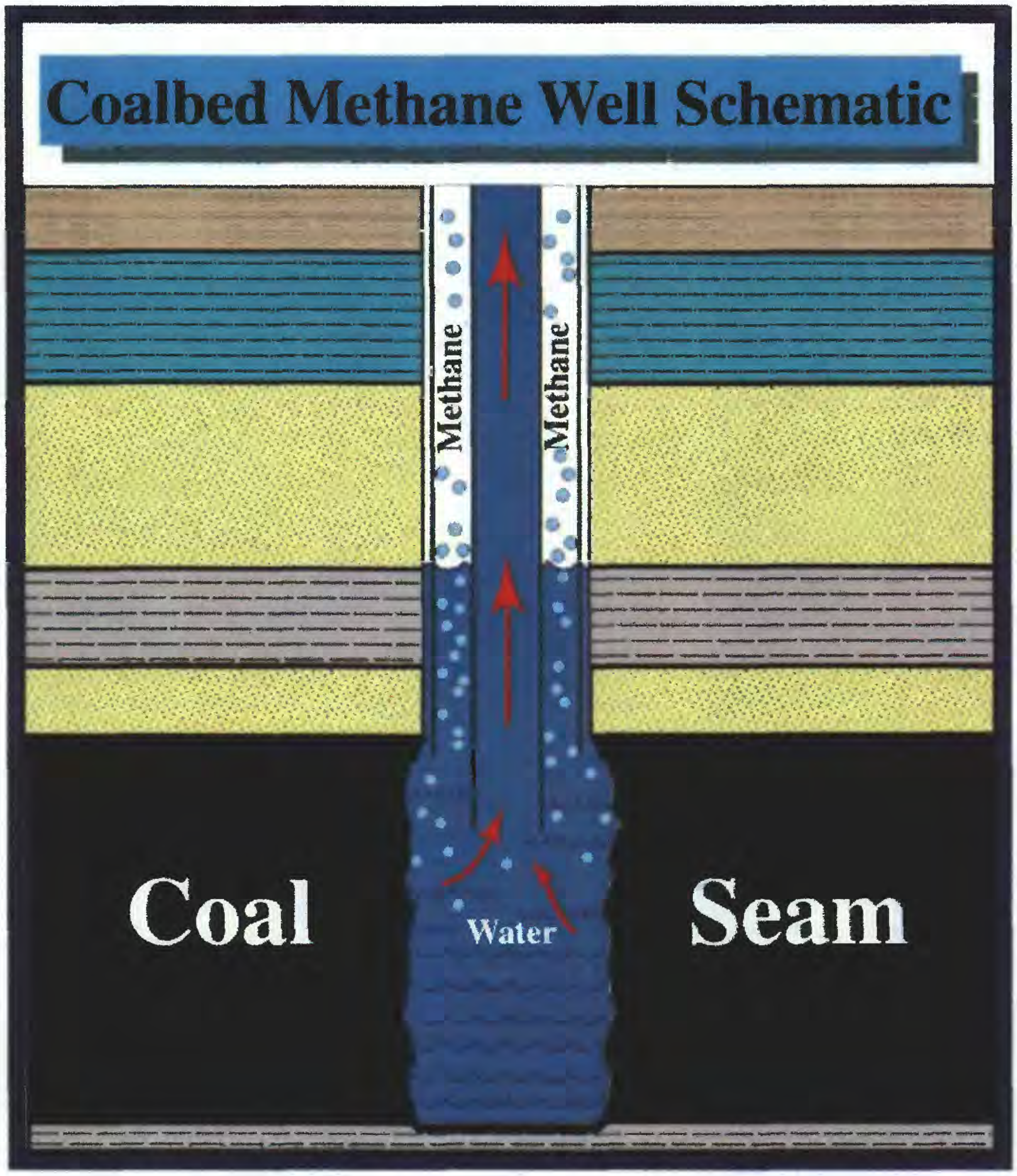

Coalbed Methane Well Schematic
Methane
Methane
Coal
Water
Seam

Figure 11

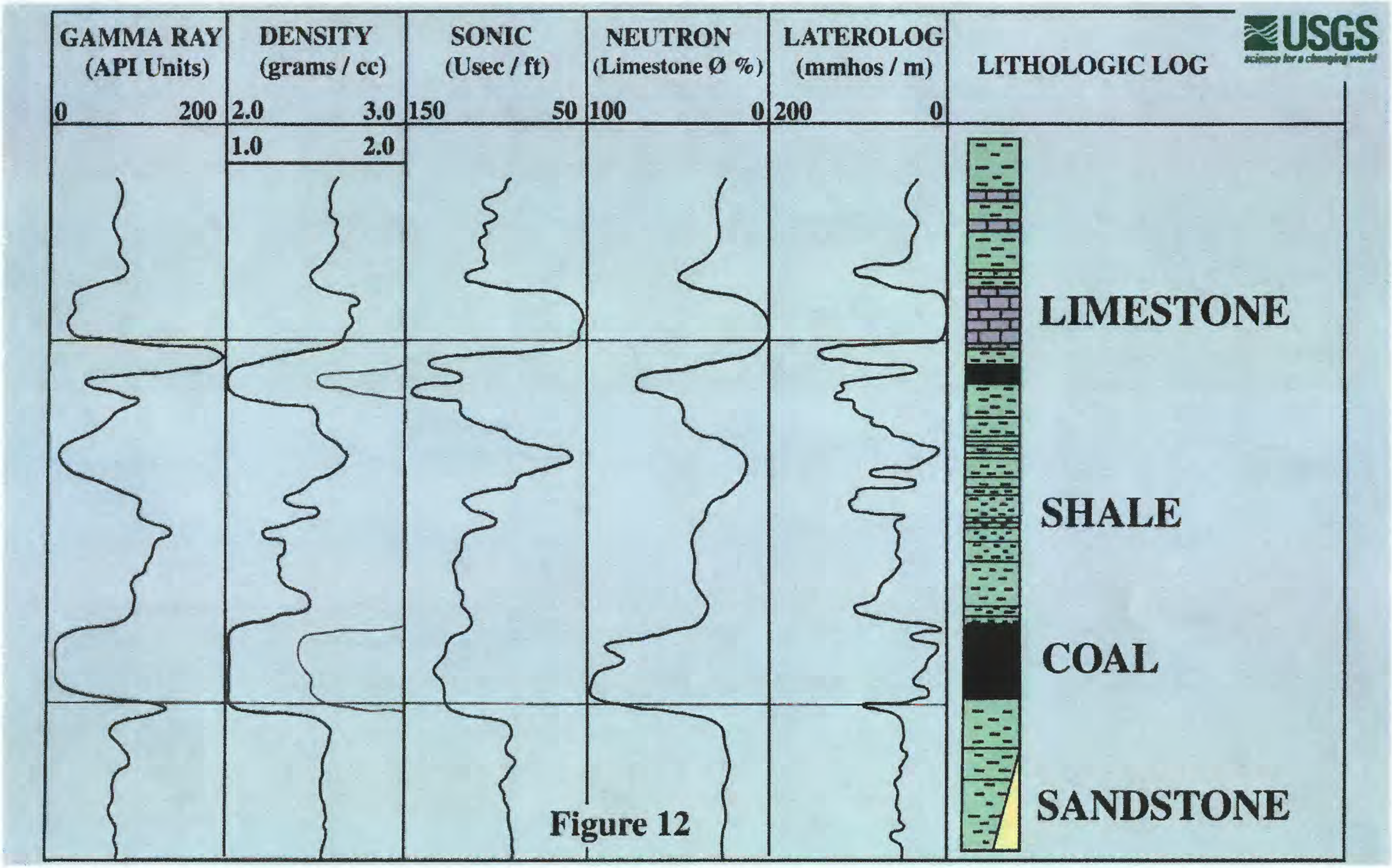
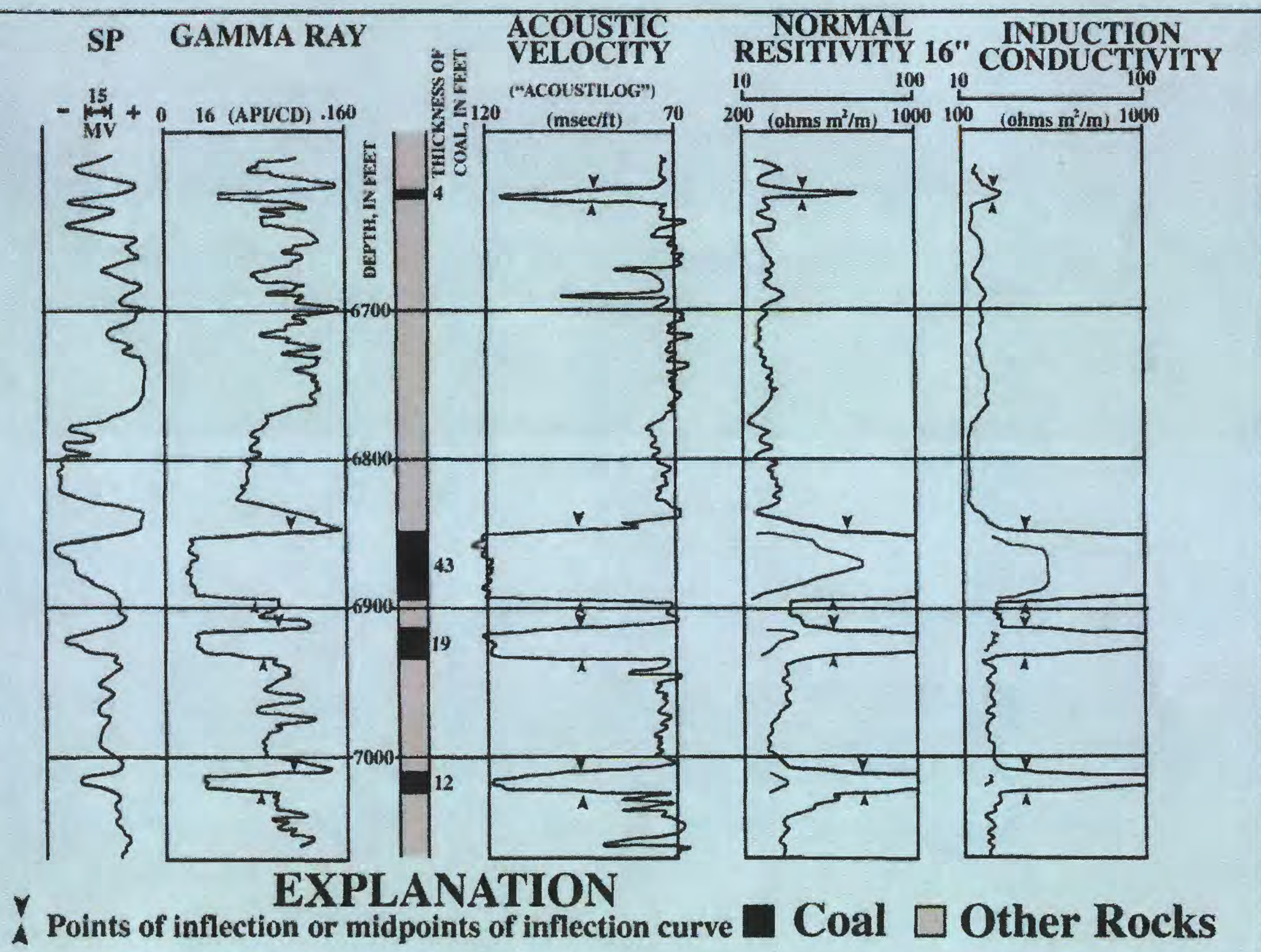
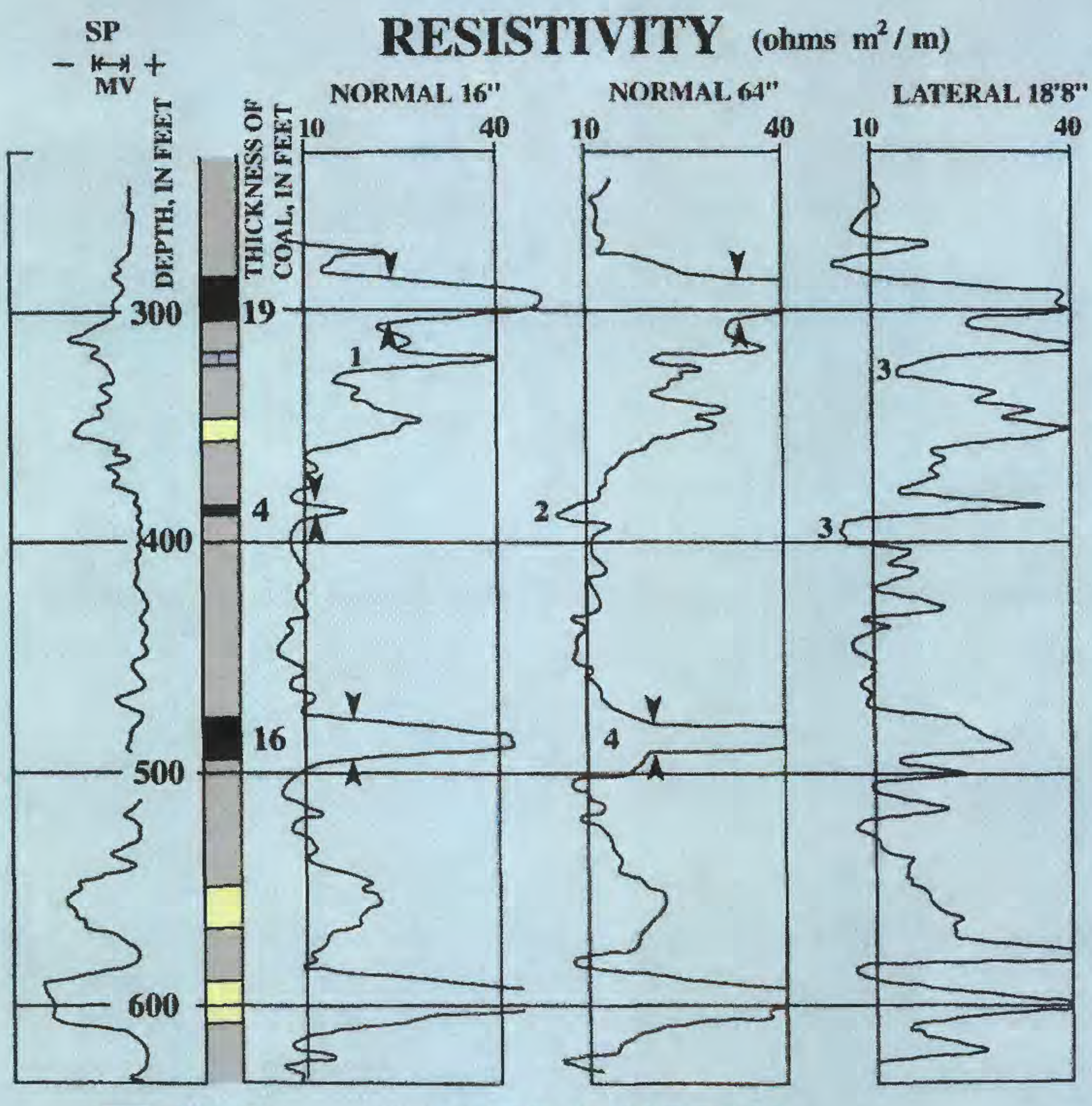

GAMMA RAY
(API Units)
0 200
DENSITY
(grams / cc)
2.0 3.0
1.0 2.0
SONIC
(Usec / ft)
150 50
NEUTRON
(Limestone Ø %)
100 0
LATEROLOG
(mmhos / m)
200 0
LITHOLOGIC LOG
USGS
science for a changing world
LIMESTONE
SHALE
COAL
SANDSTONE

Figure 12



USGS
science for a changing world

Figure 13



EXPLANATION

- Coal
- Limestone
- Sandstone
- Other Rocks

Points of inflection or midpoints of inflection curve

Figure 14

STRATIGRAPHY

Stratifact 4
Diagrammatic Column
For Database:
Assessment: Powder River Basin
Class: Stratigraphy

PRIME ZONE	SUB ZONE
QAL TW/ (Wasatch) TW/TFU? TFU/and-Wyodak TFU/UNDIFF. TFT K/Lance-FH-ALMD. Zone	Anderson Anderson-Dietz Brewster-Arnold Burley Calvert Carlson Carney Cook
Fort Union	Cook-Otter Dietz 1 Dietz 2 Dietz 3 Flowers-Goodale Kirby Lower Anderson Lower Canyon

Figure 15

Bbsnum 09DC: "Rojo 160" Drill Hole/Ron Johnson 1500.00' Undeviated

Thickness	Prim. Lith.	Interpretation Class: Lith Mod	Assessment Prime Zone	Subzone 1
184.00	MDST		TW/ (Wasatch)	
9.00	COAL		TW/ (Wasatch)	
52.00	MDST		TW/ TFU	
80.00	SS		TW/ TFU	
90.00	MDST		TW/ TFU	
25.00	SS		TW/ TFU	
9.00	MDST		TW/ TFU	
37.00	COAL		TFU/ Anderson-Wyodak	
151.00	MDST		TFU/ Anderson-Wyodak	
38.00	COAL		TFU/ Anderson-Wyodak	
80.00	MDST		TFU/ UNDIFF.	
33.00	SS		TFU/ UNDIFF.	
12.00	MDST		TFU/ UNDIFF.	
45.00	SS		TFU/ UNDIFF.	
278.00	MDST		TFU/ UNDIFF.	
47.00	SS		TFU/ UNDIFF.	
300.00	MDST		TFU/ UNDIFF.	
12.00	COAL		TFU/ UNDIFF.	
18.00	MDST		TFU/ UNDIFF.	

Figure 16

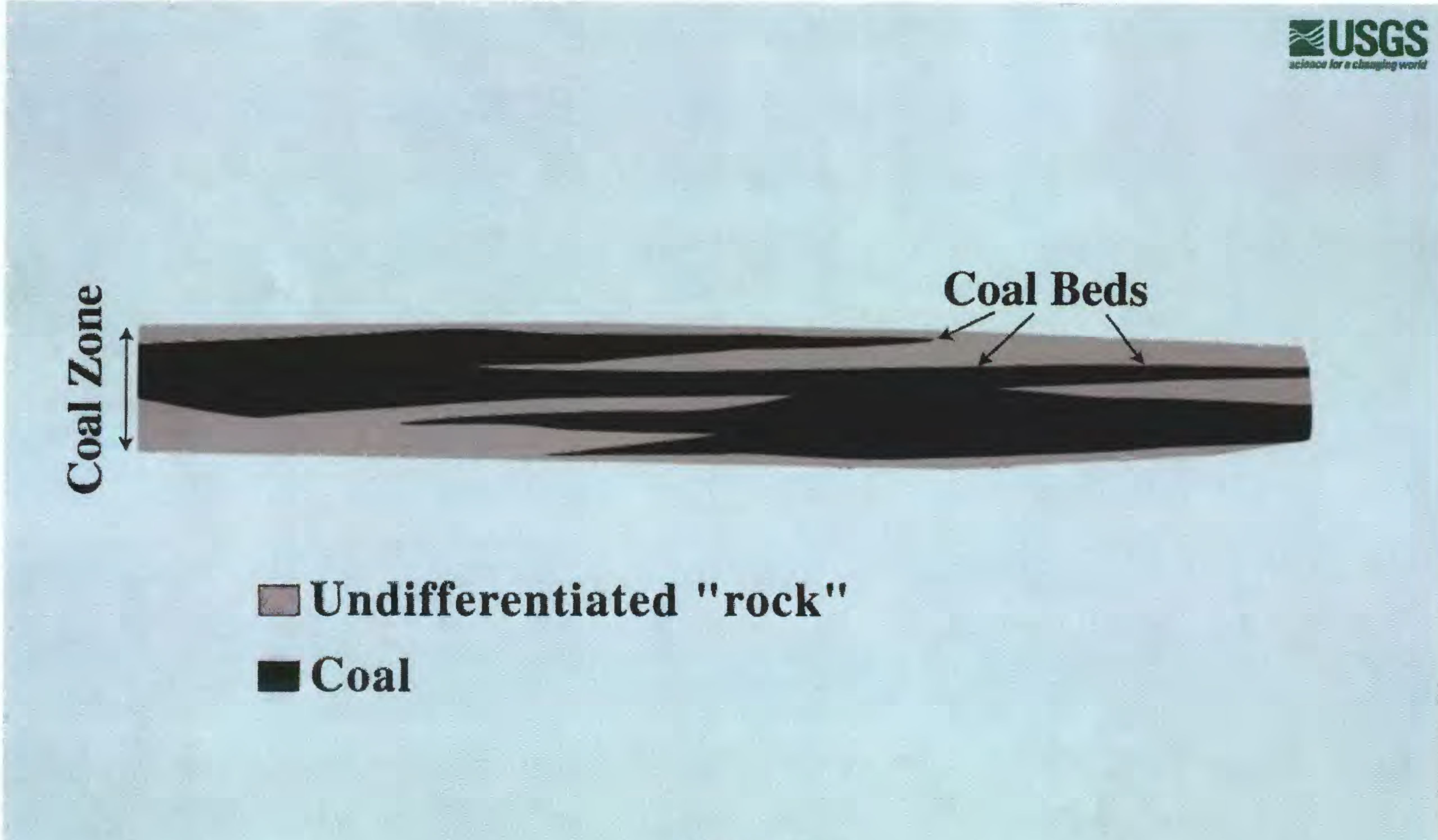

USGS
science for a changing world
Coal Beds
Coal Zone
Undifferentiated "rock"
Coal

Figure 17

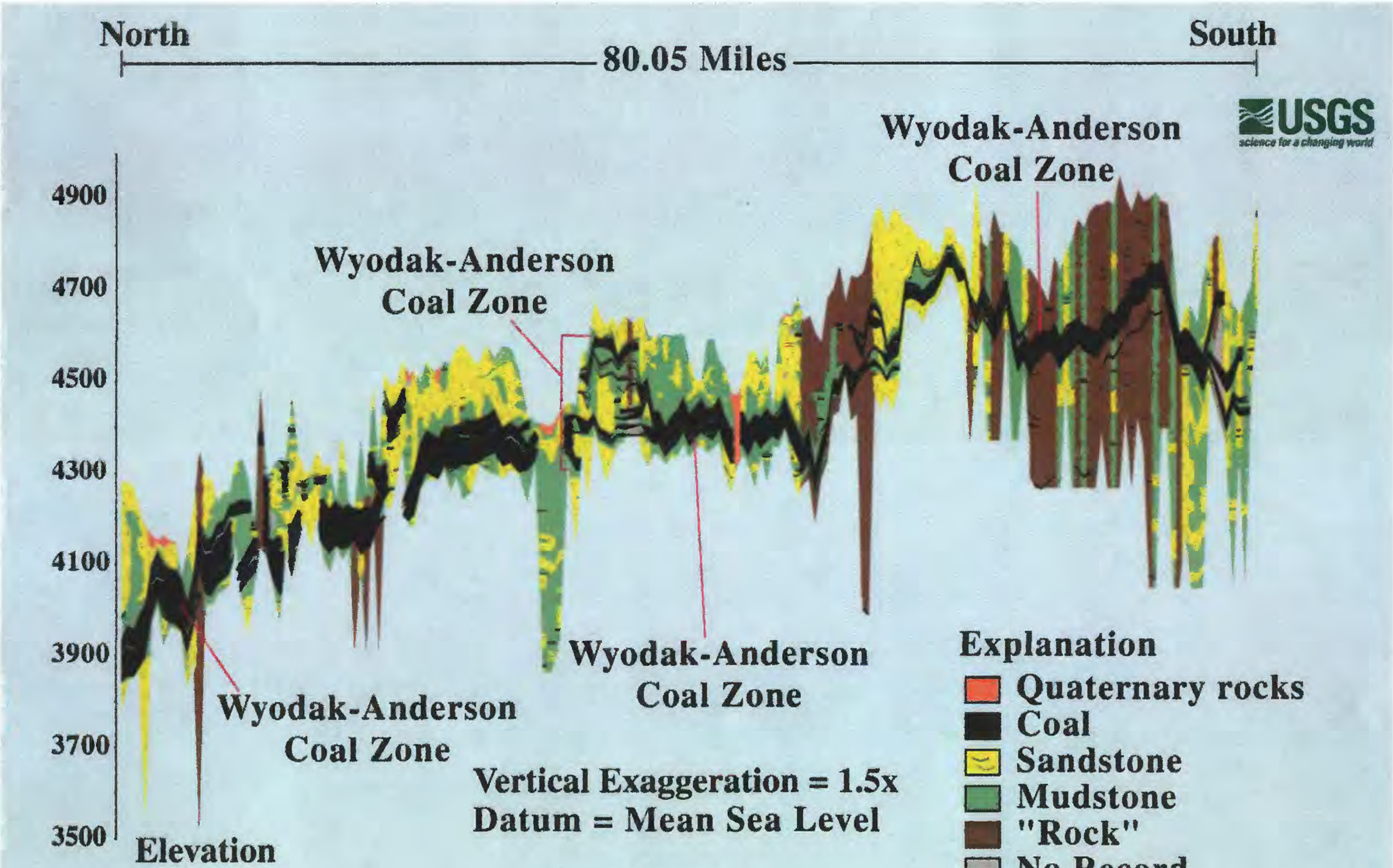

North
80.05 Miles
South
USGS
science for a changing world
4900
4700
4500
4300
4100
3900
3700
3500
Elevation
(ft)
Wyodak-Anderson
Coal Zone
Wyodak-Anderson
Coal Zone
Wyodak-Anderson
Coal Zone
Wyodak-Anderson
Coal Zone
Vertical Exaggeration = 1.5x
Datum = Mean Sea Level
Explanation
Quaternary rocks
Coal
Sandstone
Mudstone
"Rock"
No Record

Figure 18

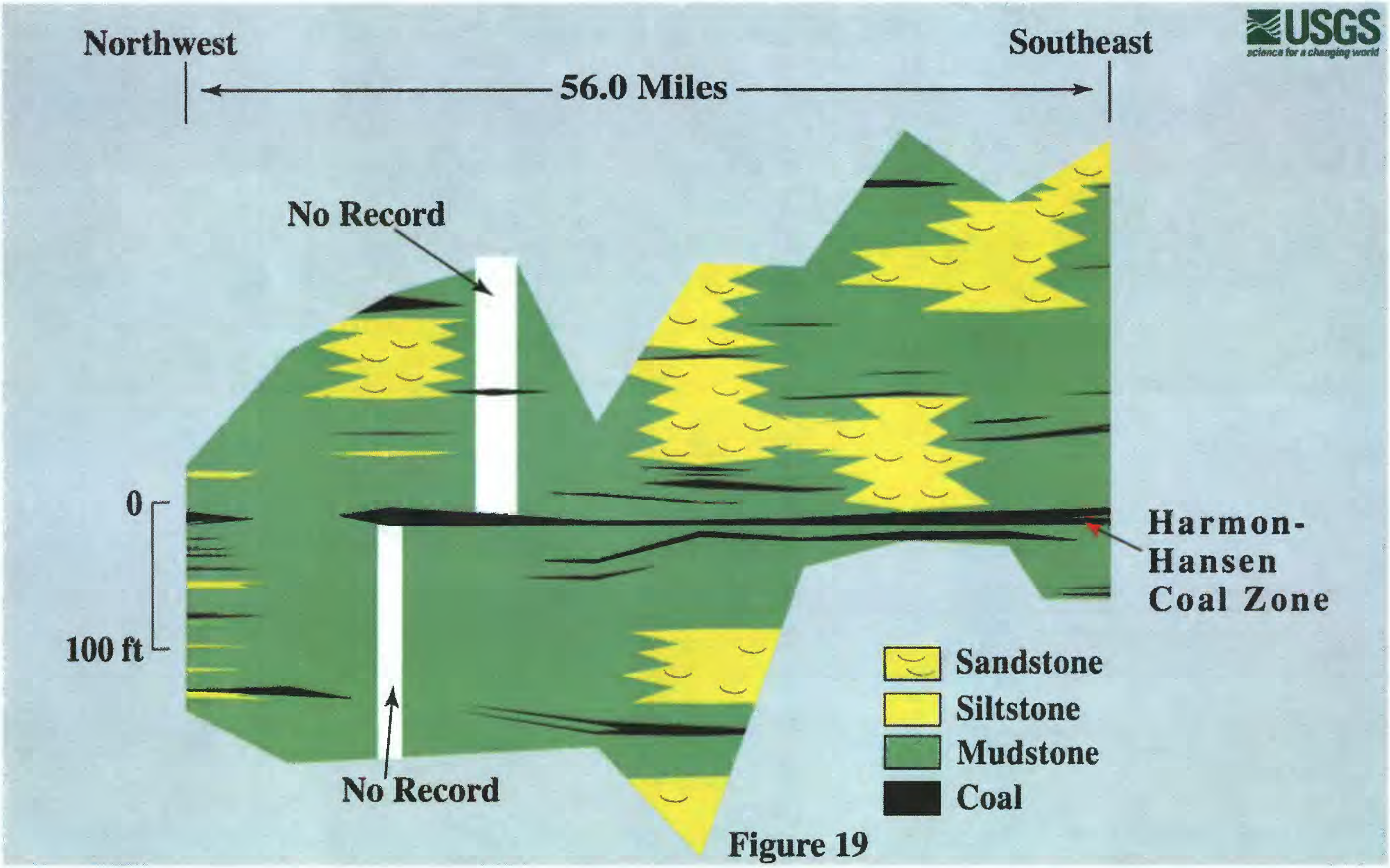

Northwest
Southeast
56.0 Miles
No Record
No Record
0
100 ft
Harmon-
Hansen
Coal Zone
Sandstone
Siltstone
Mudstone
Coal
USGS
science for a changing world

Figure 19

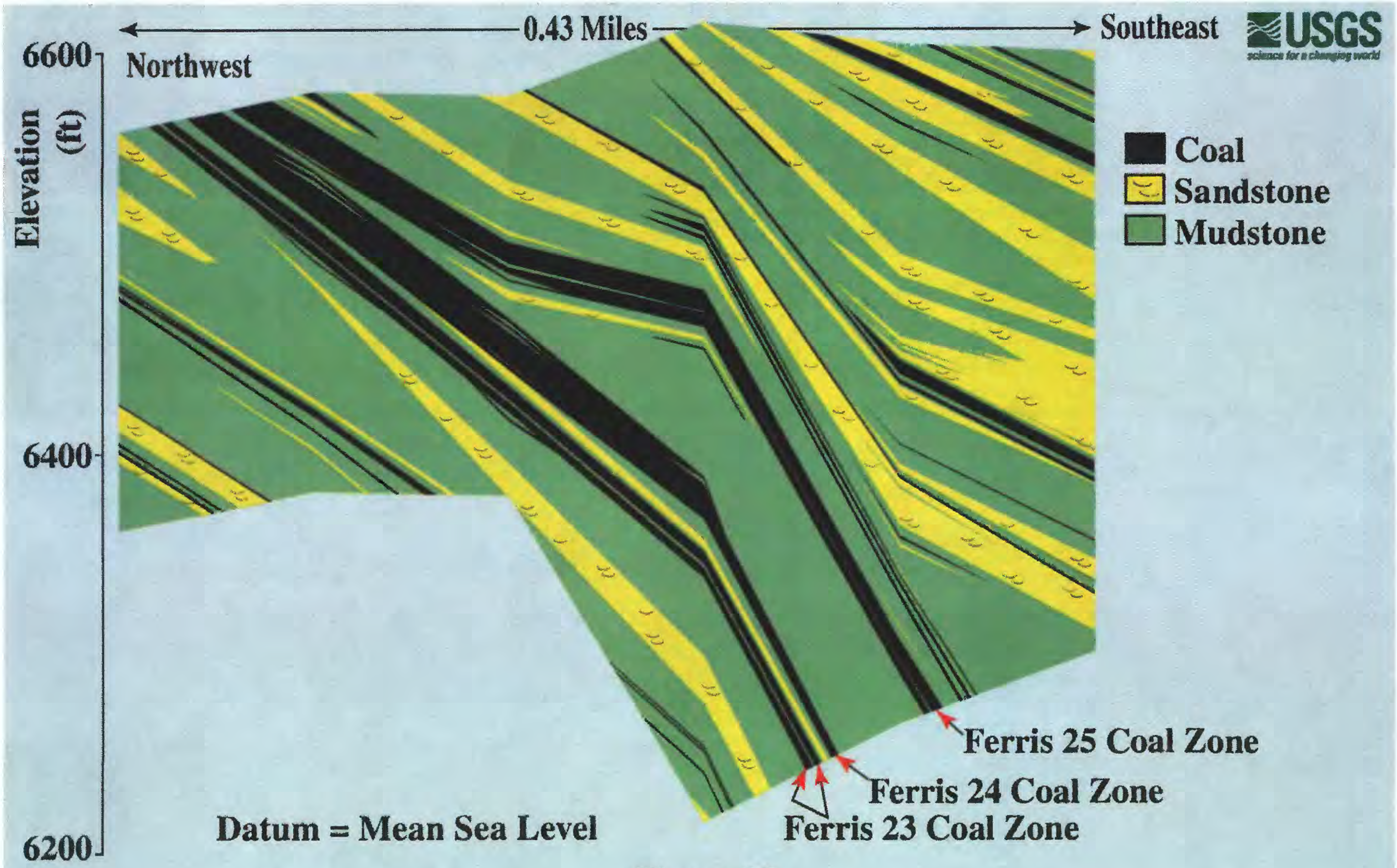

0.43 Miles
Northwest
Southeast
USGS
science for a changing world
Elevation (ft)
6600
6400
6200
Coal
Sandstone
Mudstone
Ferris 25 Coal Zone
Ferris 24 Coal Zone
Ferris 23 Coal Zone
Datum = Mean Sea Level

Figure 20

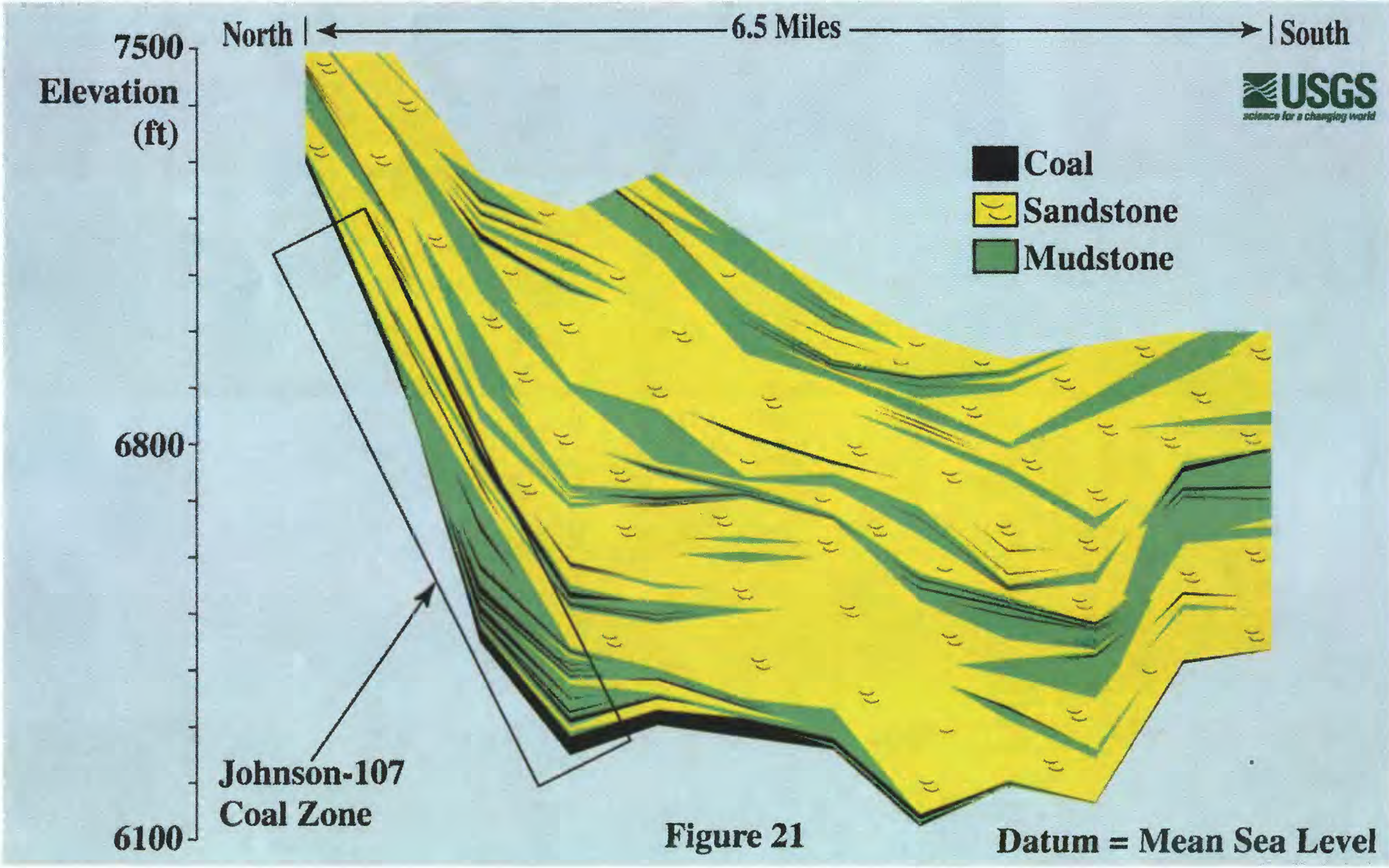

North
6.5 Miles
South
7500
Elevation
(ft)
6800
6100
USGS
science for a changing world
Coal
Sandstone
Mudstone
Johnson-107
Coal Zone
Datum = Mean Sea Level

Figure 21

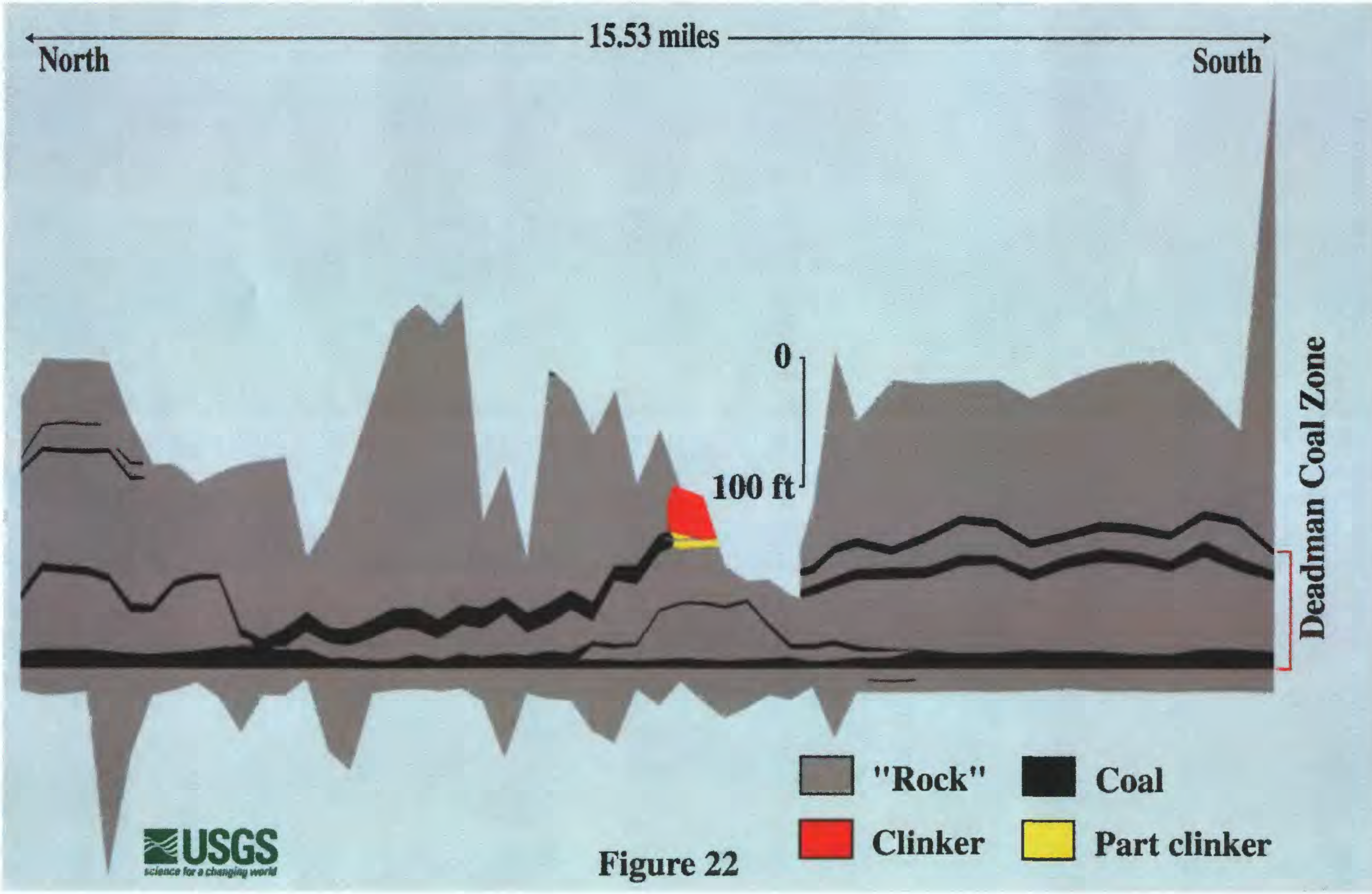

15.53 miles
North
South
0
100 ft
Deadman Coal Zone
"Rock"
Coal
Clinker
Part clinker
USGS
science for a changing world

Figure 22

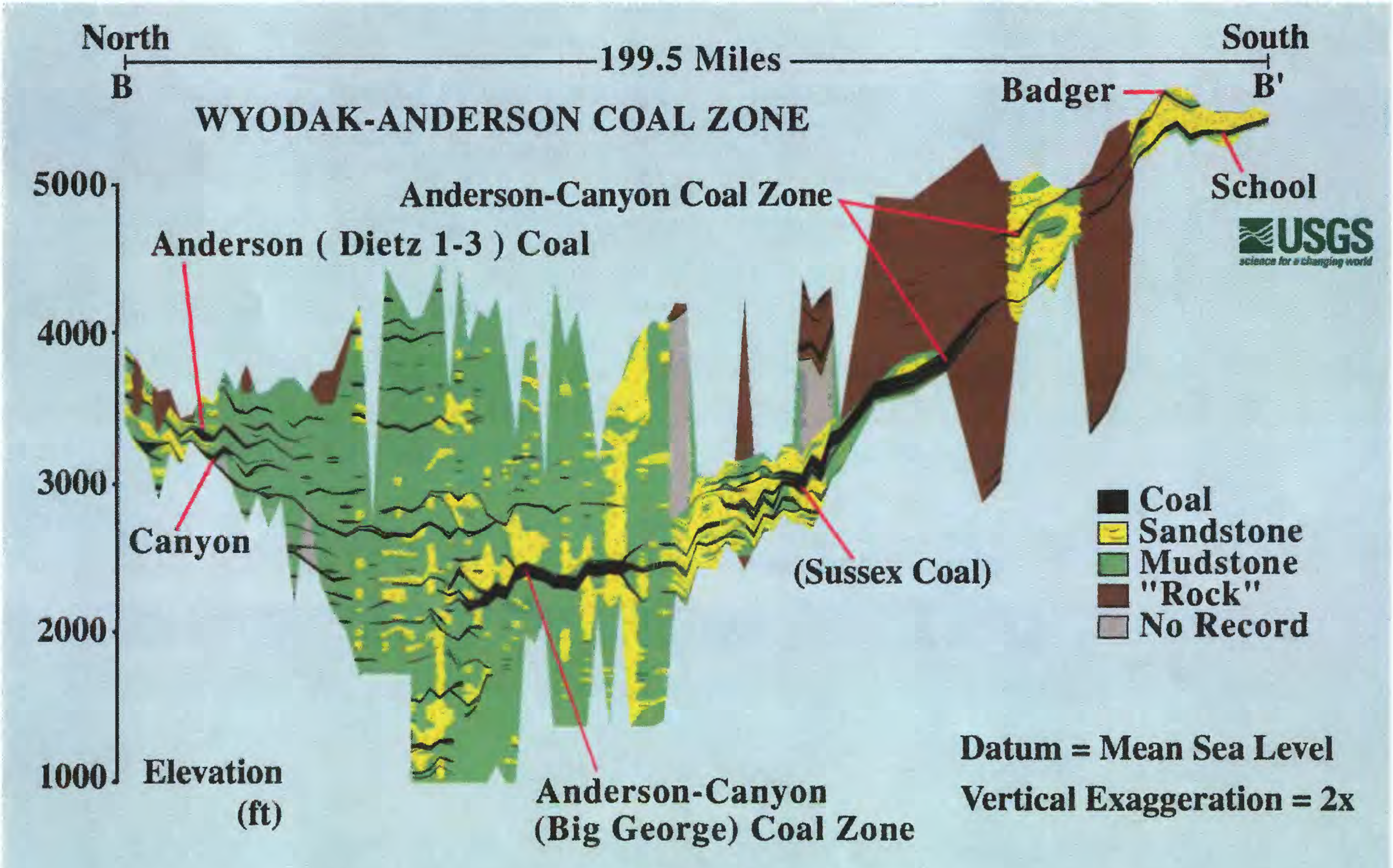
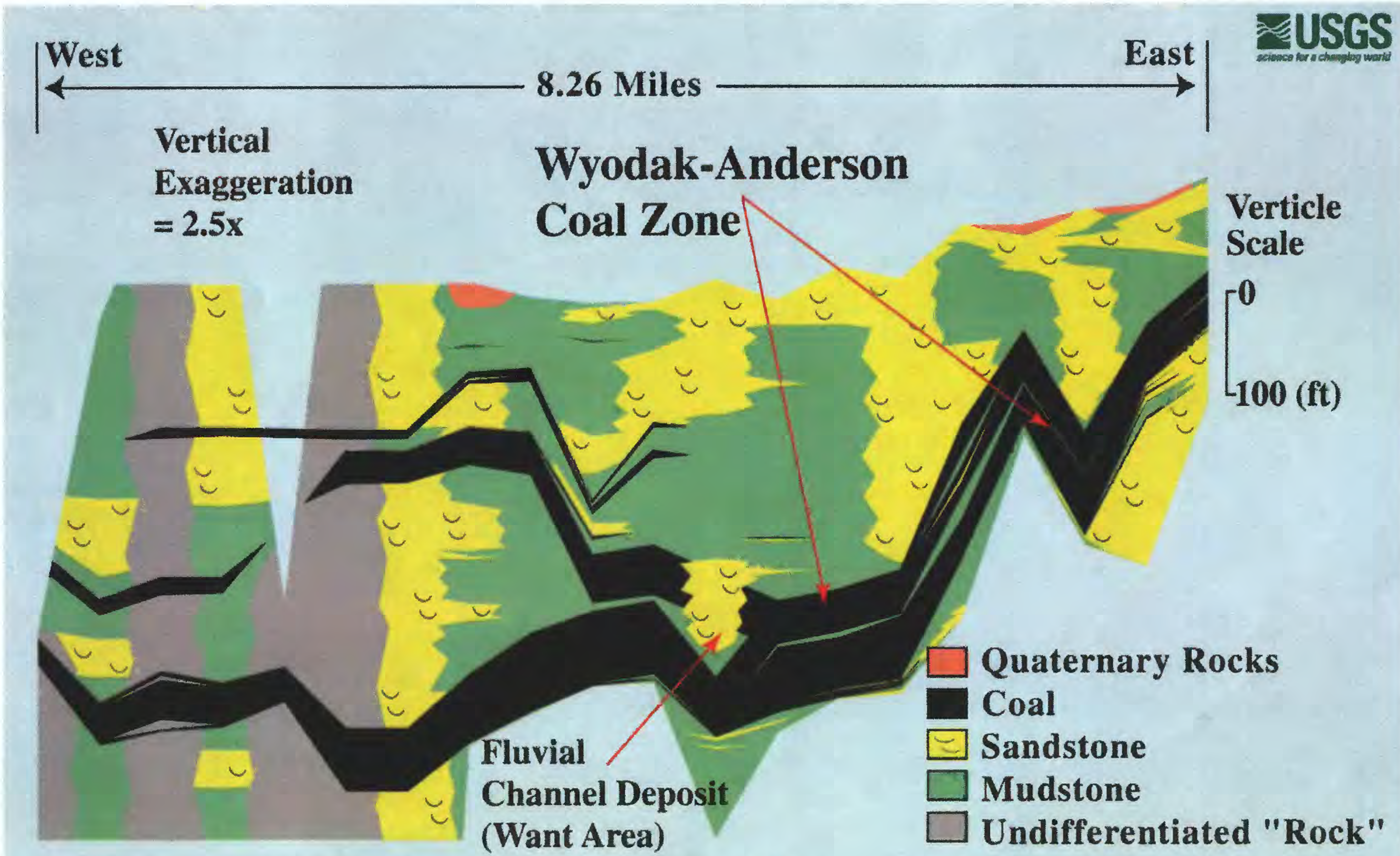
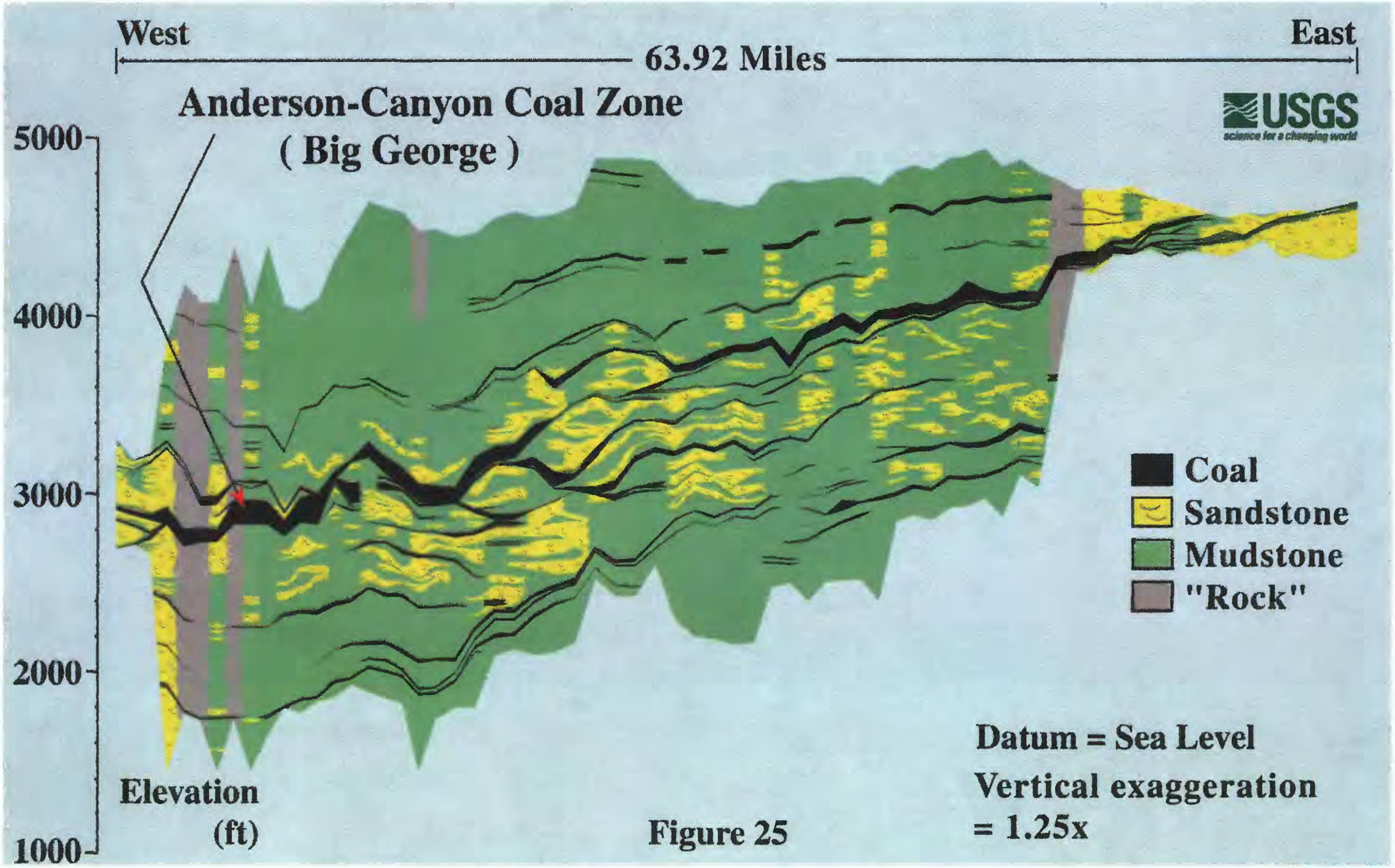

North
South
B
B'
199.5 Miles
WYODAK-ANDERSON COAL ZONE
Badger
School
Anderson-Canyon Coal Zone
Anderson (Dietz 1-3) Coal
Canyon
(Sussex Coal)
Anderson-Canyon
(Big George) Coal Zone
5000
4000
3000
2000
1000
Elevation
(ft)
Coal
Sandstone
Mudstone
"Rock"
No Record
Datum = Mean Sea Level
Vertical Exaggeration = 2x
USGS
science for a changing world

Figure 23



West
East
8.26 Miles
Vertical Exaggeration = 2.5x
Wyodak-Anderson Coal Zone
Verticle Scale
0
100 (ft)
Fluvial Channel Deposit (Want Area)
Quaternary Rocks
Coal
Sandstone
Mudstone
Undifferentiated "Rock"

Figure 24



West
East
63.92 Miles
Anderson-Canyon Coal Zone
(Big George)
USGS
science for a changing world
5000
4000
3000
2000
1000
Elevation
(ft)
Coal
Sandstone
Mudstone
"Rock"
Datum = Sea Level
Vertical exaggeration
= 1.25x

Figure 25

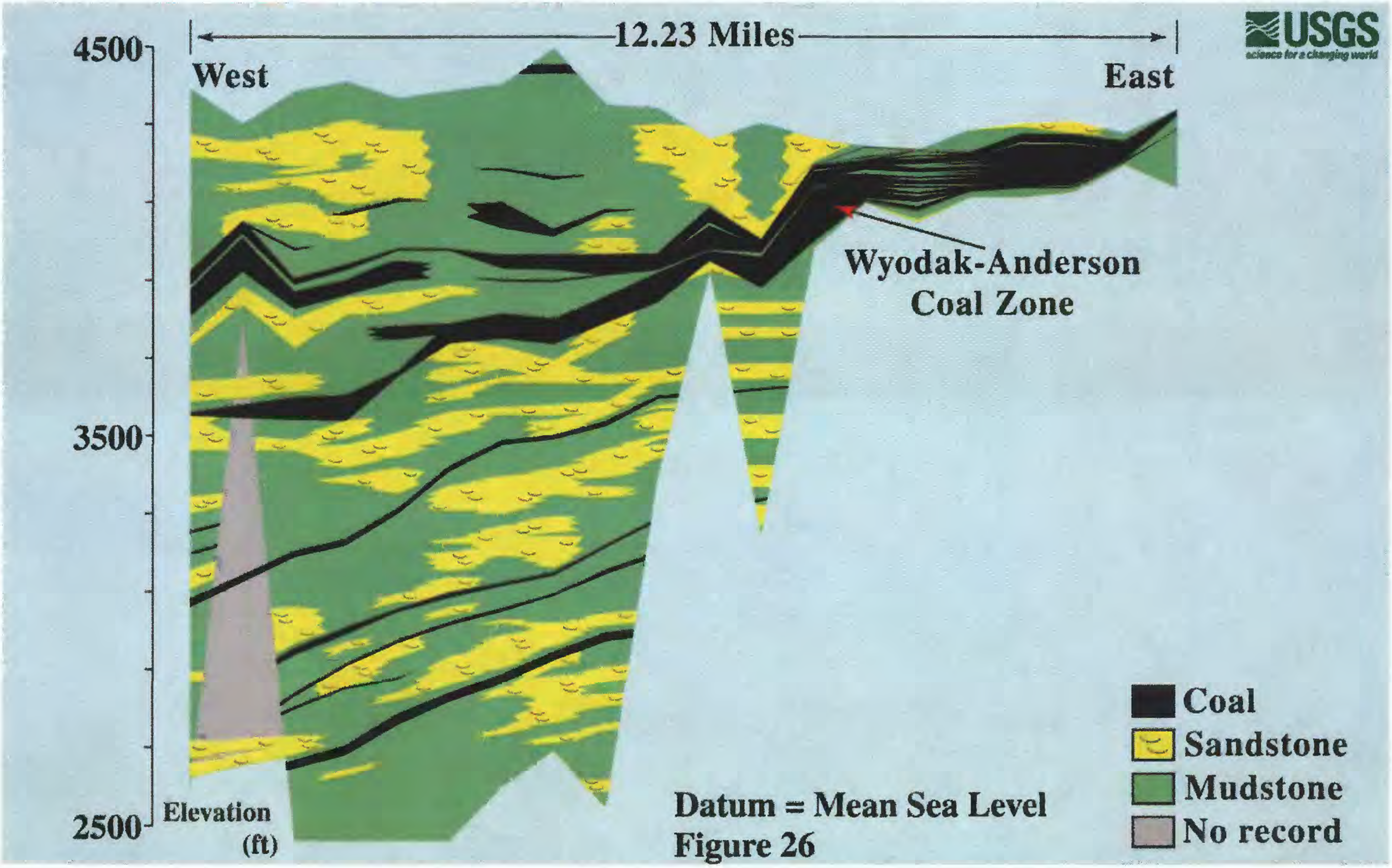

12.23 Miles
West
East
USGS
science for a changing world
4500
3500
2500
Elevation
(ft)
Wyodak-Anderson
Coal Zone
Datum = Mean Sea Level
Coal
Sandstone
Mudstone
No record

Figure 26

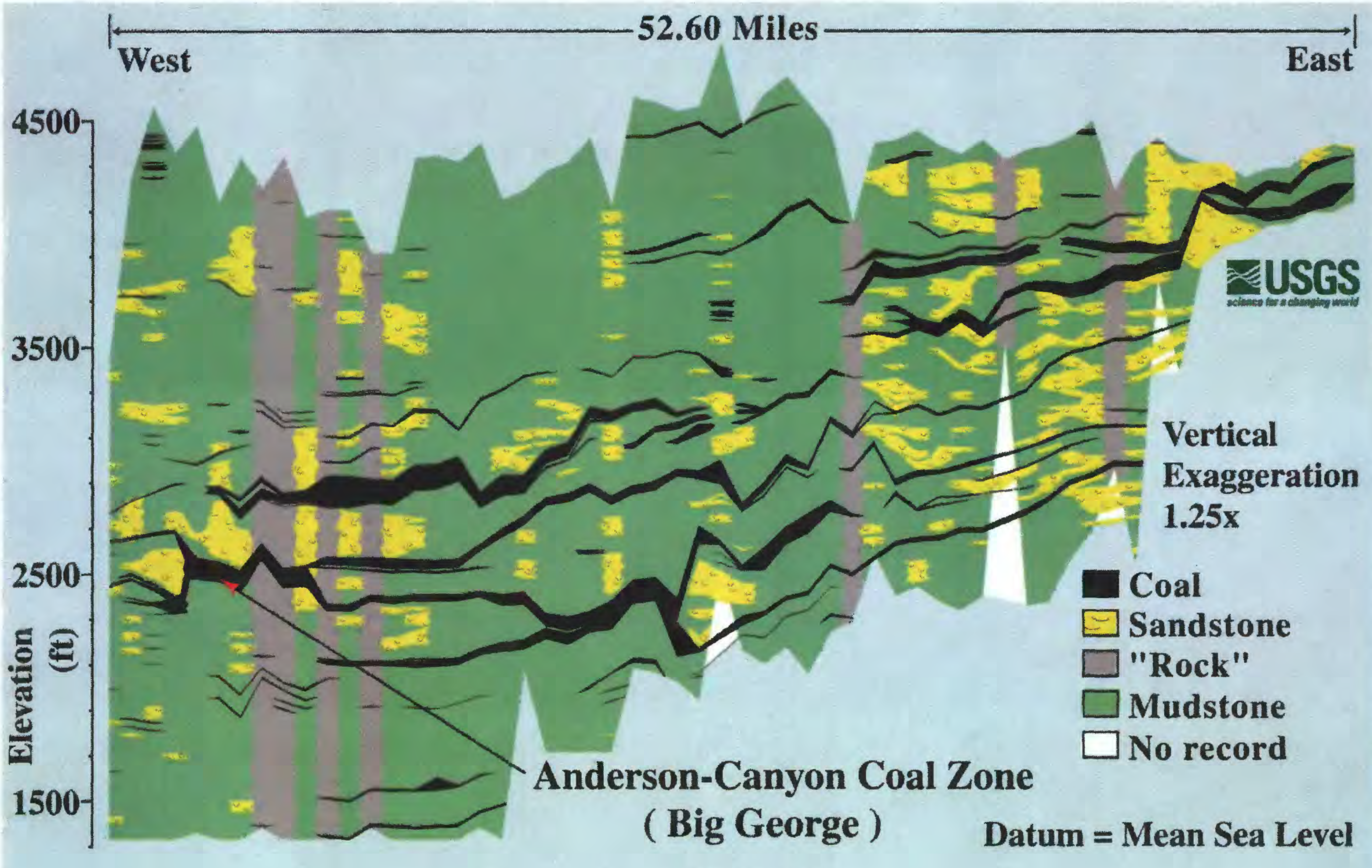

52.60 Miles
West
East
4500
3500
2500
1500
Elevation (ft)
USGS
science for a changing world
Vertical Exaggeration 1.25x
Coal
Sandstone
"Rock"
Mudstone
No record
Anderson-Canyon Coal Zone
(Big George)
Datum = Mean Sea Level

Figure 27

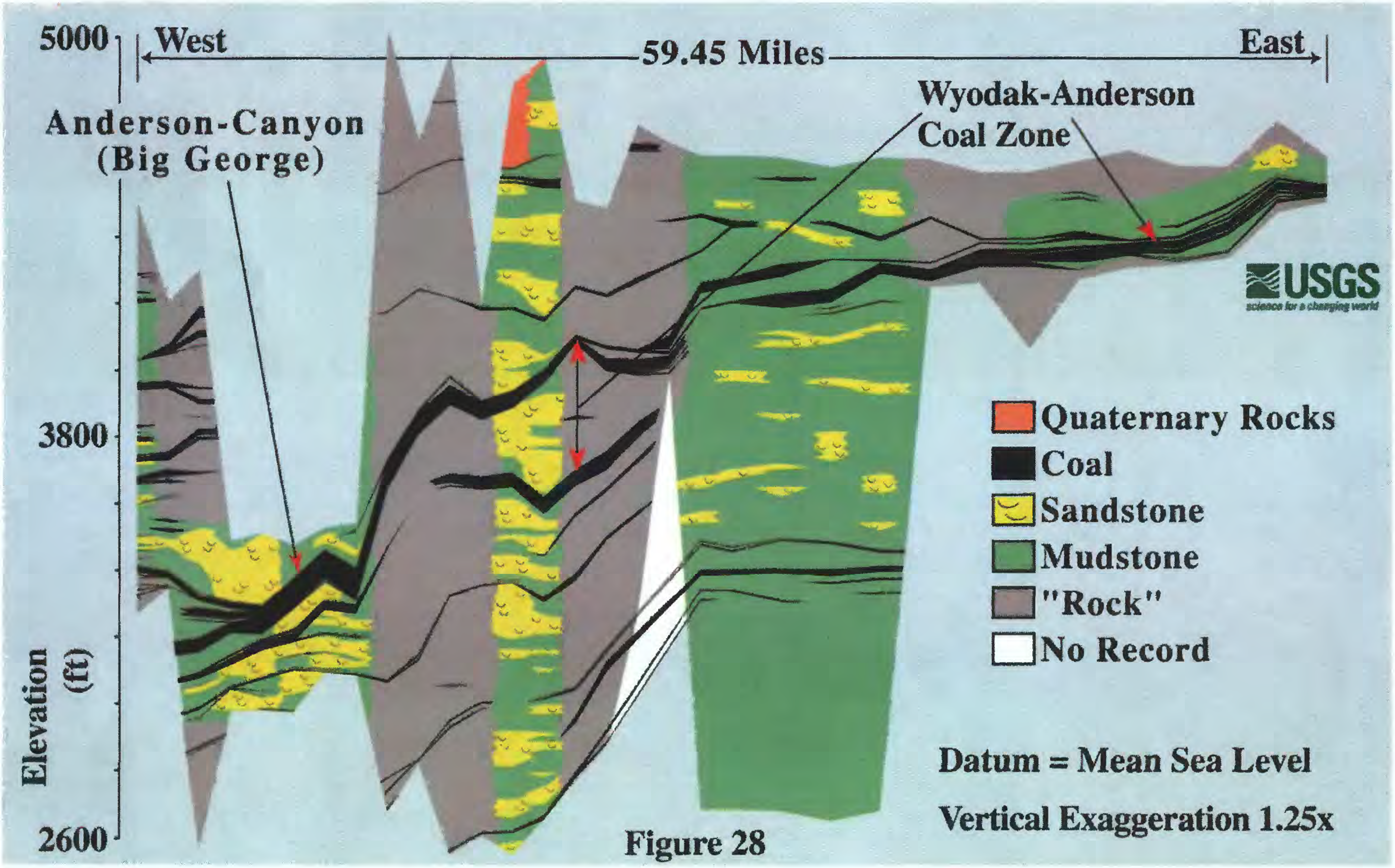

5000
3800
2600
Elevation (ft)
West
59.45 Miles
East
Anderson-Canyon
(Big George)
Wyodak-Anderson
Coal Zone
USGS
science for a changing world
Quaternary Rocks
Coal
Sandstone
Mudstone
"Rock"
No Record
Datum = Mean Sea Level
Vertical Exaggeration 1.25x

Figure 28

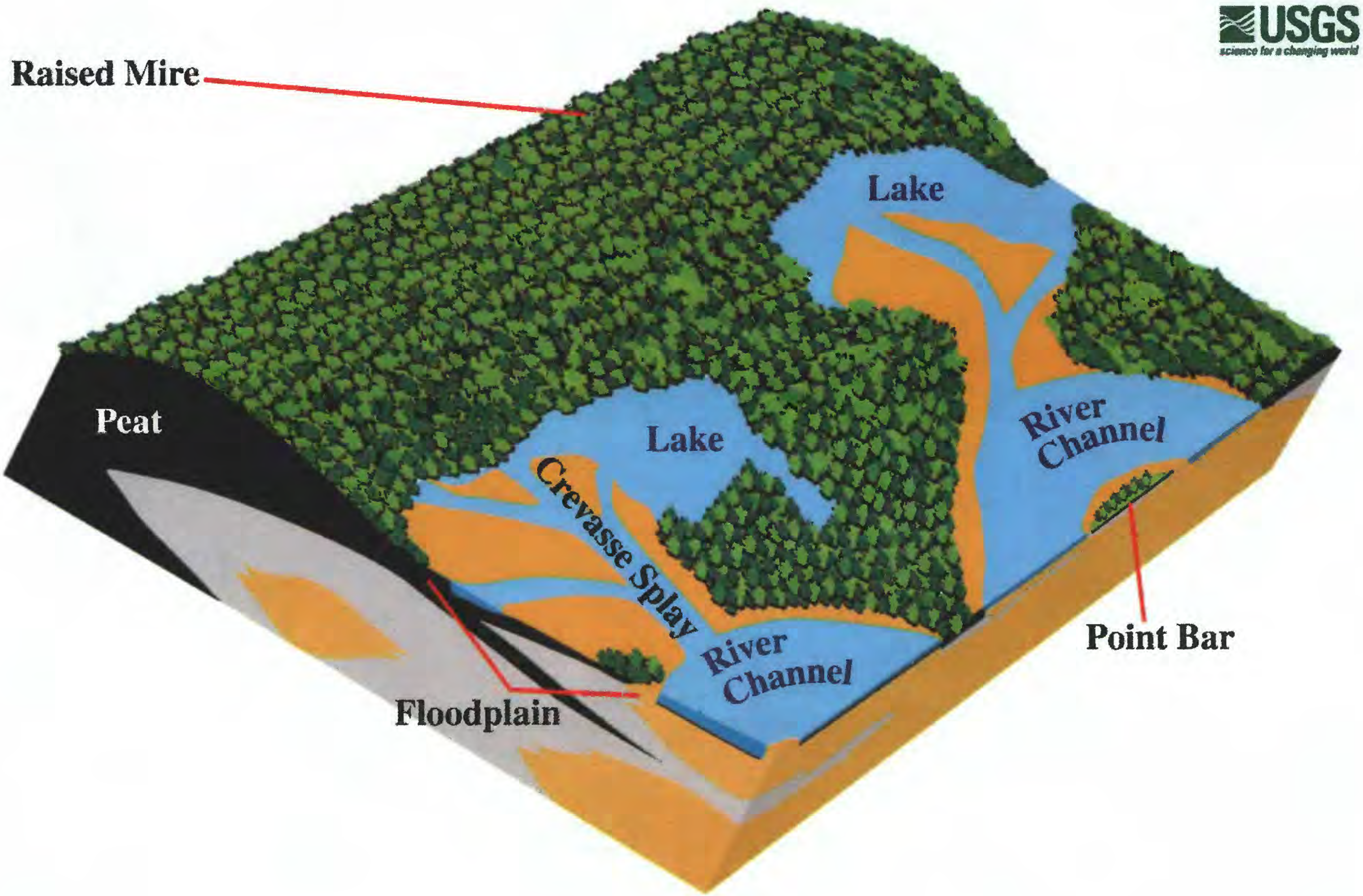

USGS
science for a changing world
Raised Mire
Peat
Lake
Lake
Crevasse Splay
River Channel
River Channel
Point Bar
Floodplain

Figure 29

Figure 30

Figure 31

Figure 32

USGS
science for a changing world

Figure 33

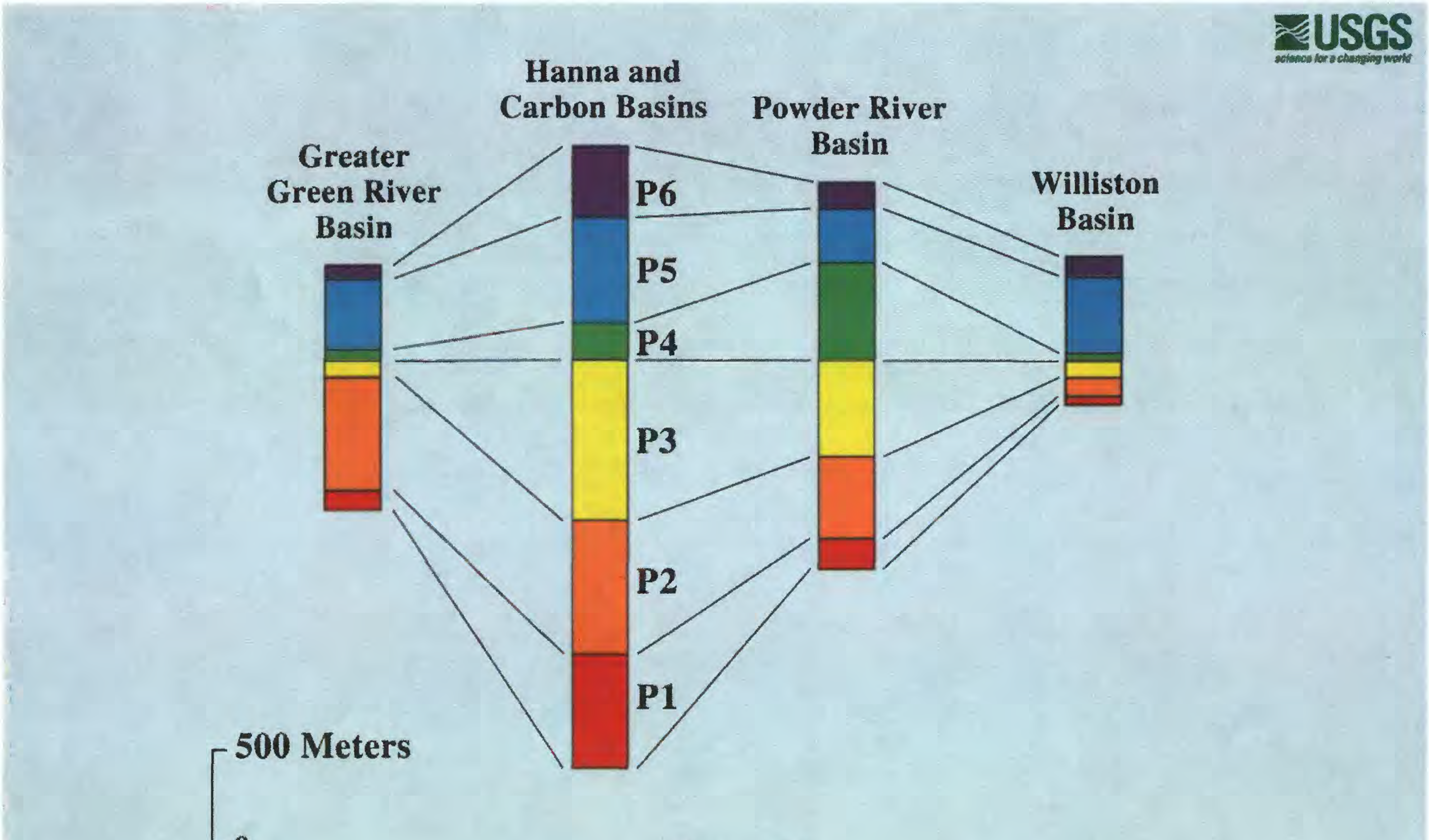

USGS
science for a changing world
Greater
Green River
Basin
Hanna and
Carbon Basins
Powder River
Basin
Williston
Basin
P6
P5
P4
P3
P2
P1
500 Meters
0

Figure 34

Interval and Lab sheet

USGS science for a changing world

Sample ID		DBSN Point/Well ID		Basis as received	
049Z - 0001		049Z 1 - 4		Lab sheet as received	
Top	389.00	Bottom	399.00	Date	Time
				/ /	:

Measurements

Constituent	Value
BTU Per Pound	9370
Moist Mineral Matter Free BTU/lb	10050
Moisture	22
Volatile Matter	34
Fixed Carbon	38
Ash	6.2
Total Sulfur	0.9
Pounds SO_2/Million BTU	0.59
Sulfate Sulfur	0.10
Pyritic Sulfur	0.19
Organic Sulfur	0.65
Arsenic (on a whole coal basis)	4.0
Beryllium (on a whole coal basis)	0.4

Figure 35

Interval and Lab sheet

Sample ID	DBSN Point/Well ID	Basis as received
049Z - 0001	049Z 1 - 4	Lab sheet as received
Top 389.00	Bottom 399.00	Date / / Time :

Measurements

Constituent		Value
Arsenic	(on a whole coal basis)	4.000
Beryllium		0.400
Cadmium		0.090
Chlorine		0.000
Cobalt		1.580
Chromium		5.530
Mercury		0.120
Manganese		11.850
Nickel		5.530
Lead		1.980
Antimony		0.300
Selenium		0.400
Uranium	(on a whole coal basis)	0.790

Figure 36

RESOURCE CALCULATION

FORMULA FOR SUBBITUMINOUS COAL

SHORT TONS = AREA X COAL THICKNESS DENSITY X COAL RANK = 2 ACRES X 10FT X 1,770 SHORT TONS PER ACRE-FT = 35,400 SHORT TONS

Figure 37

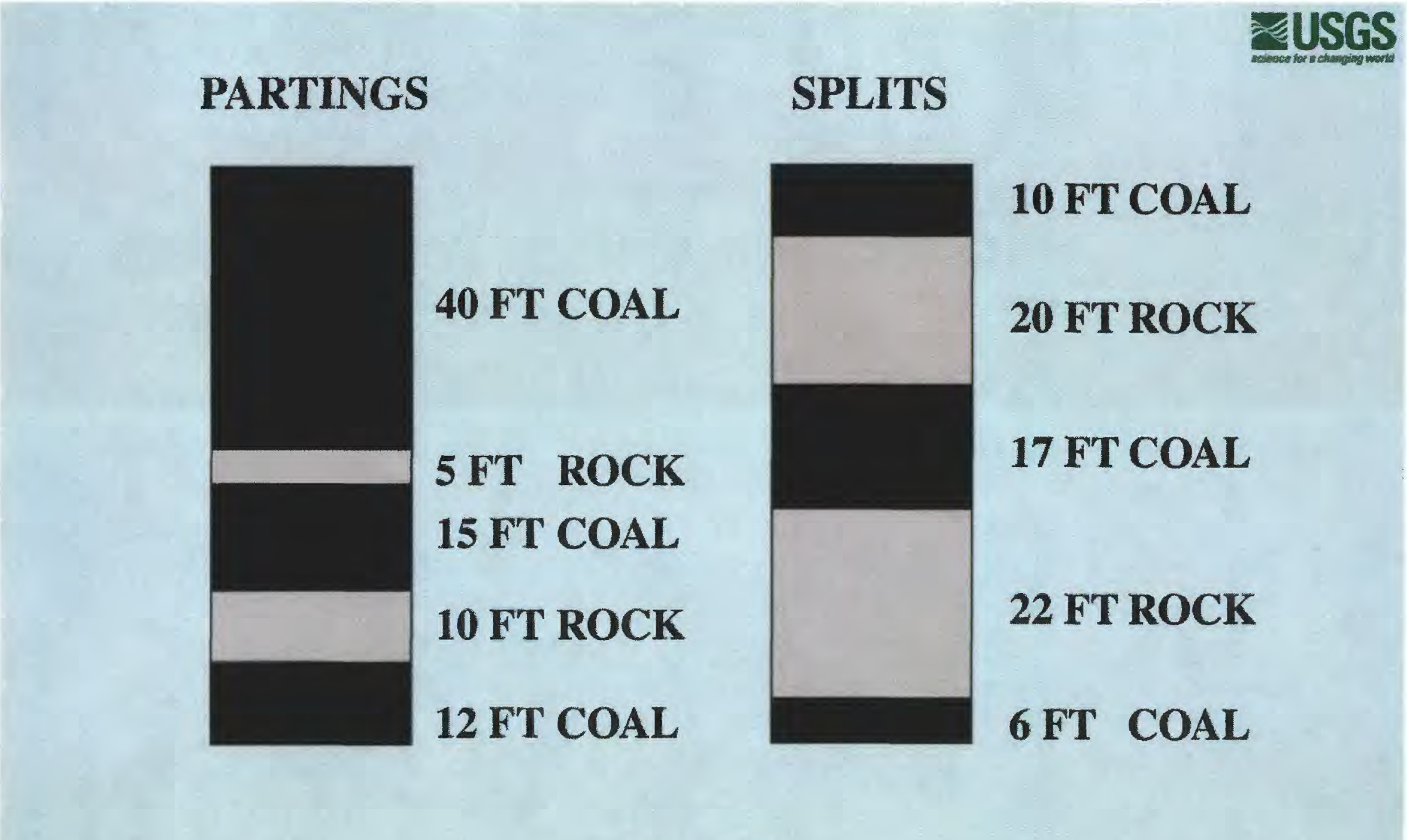

PARTINGS
40 FT COAL
5 FT ROCK
15 FT COAL
10 FT ROCK
12 FT COAL
SPLITS
10 FT COAL
20 FT ROCK
17 FT COAL
22 FT ROCK
6 FT COAL
USGS
science for a changing world

Figure 38

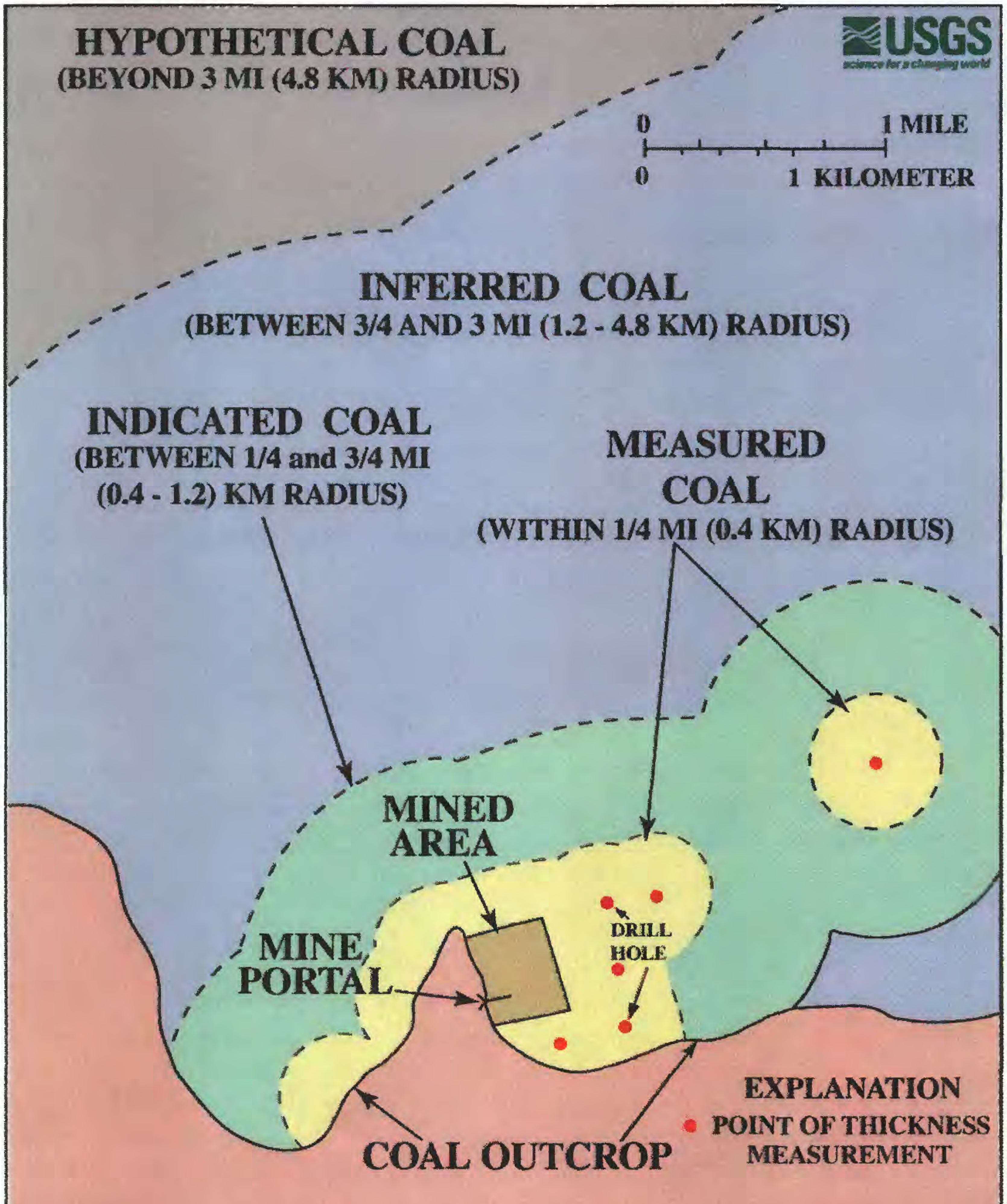

HYPOTHETICAL COAL
(BEYOND 3 MI (4.8 KM) RADIUS)
USGS
0
1 MILE
0
1 KILOMETER
INFERRED COAL
(BETWEEN 3/4 AND 3 MI (1.2 - 4.8 KM) RADIUS)
INDICATED COAL
(BETWEEN 1/4 and 3/4 MI
(0.4 - 1.2) KM RADIUS)
MEASURED
COAL
(WITHIN 1/4 MI (0.4 KM) RADIUS)
MINED
AREA
MINE
PORTAL
DRILL
HOLE
COAL OUTCROP
EXPLANATION
POINT OF THICKNESS
MEASUREMENT

Figure 39

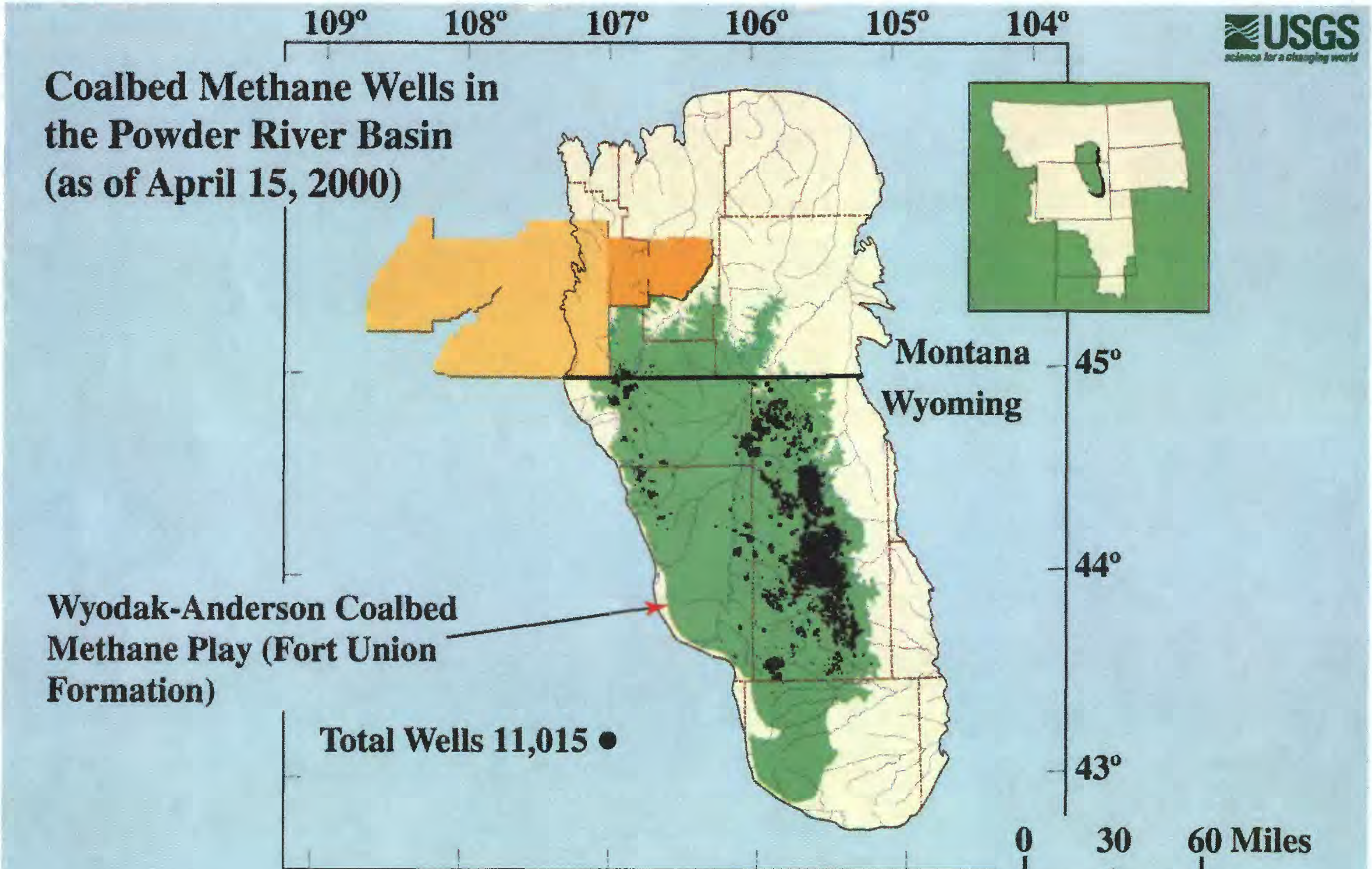

Coalbed Methane Wells in
the Powder River Basin
(as of April 15, 2000)
109°
108°
107°
106°
105°
104°
45°
44°
43°
Montana
Wyoming
Wyodak-Anderson Coalbed
Methane Play (Fort Union
Formation)
Total Wells 11,015 ●
0
30
60 Miles
USGS
science for a changing world

Figure 40

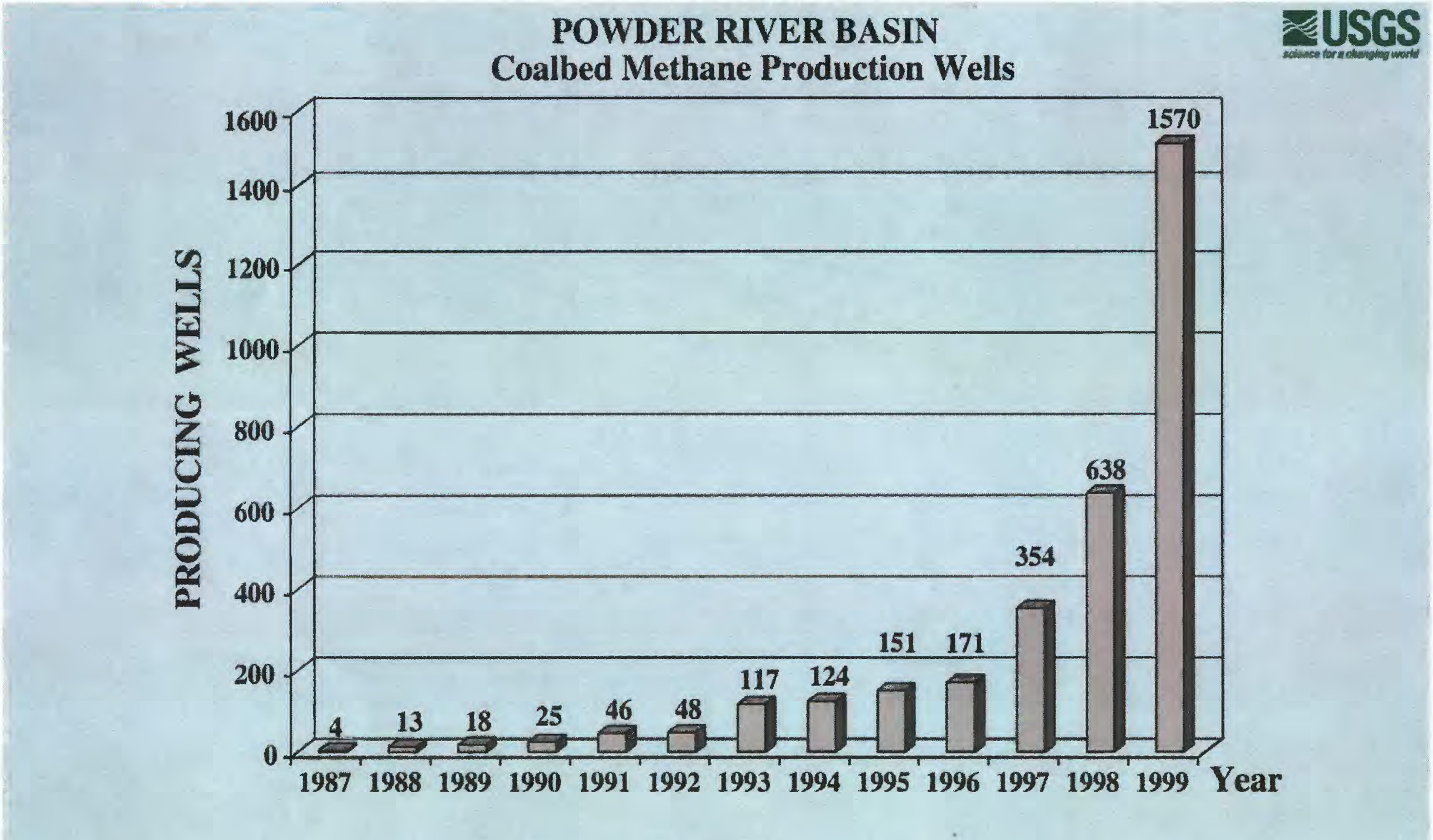

POWDER RIVER BASIN
Coalbed Methane Production Wells
USGS
science for a changing world
PRODUCING WELLS
1600
1400
1200
1000
800
600
400
200
0
4
13
18
25
46
48
117
124
151
171
354
638
1570
1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999
Year

Figure 41

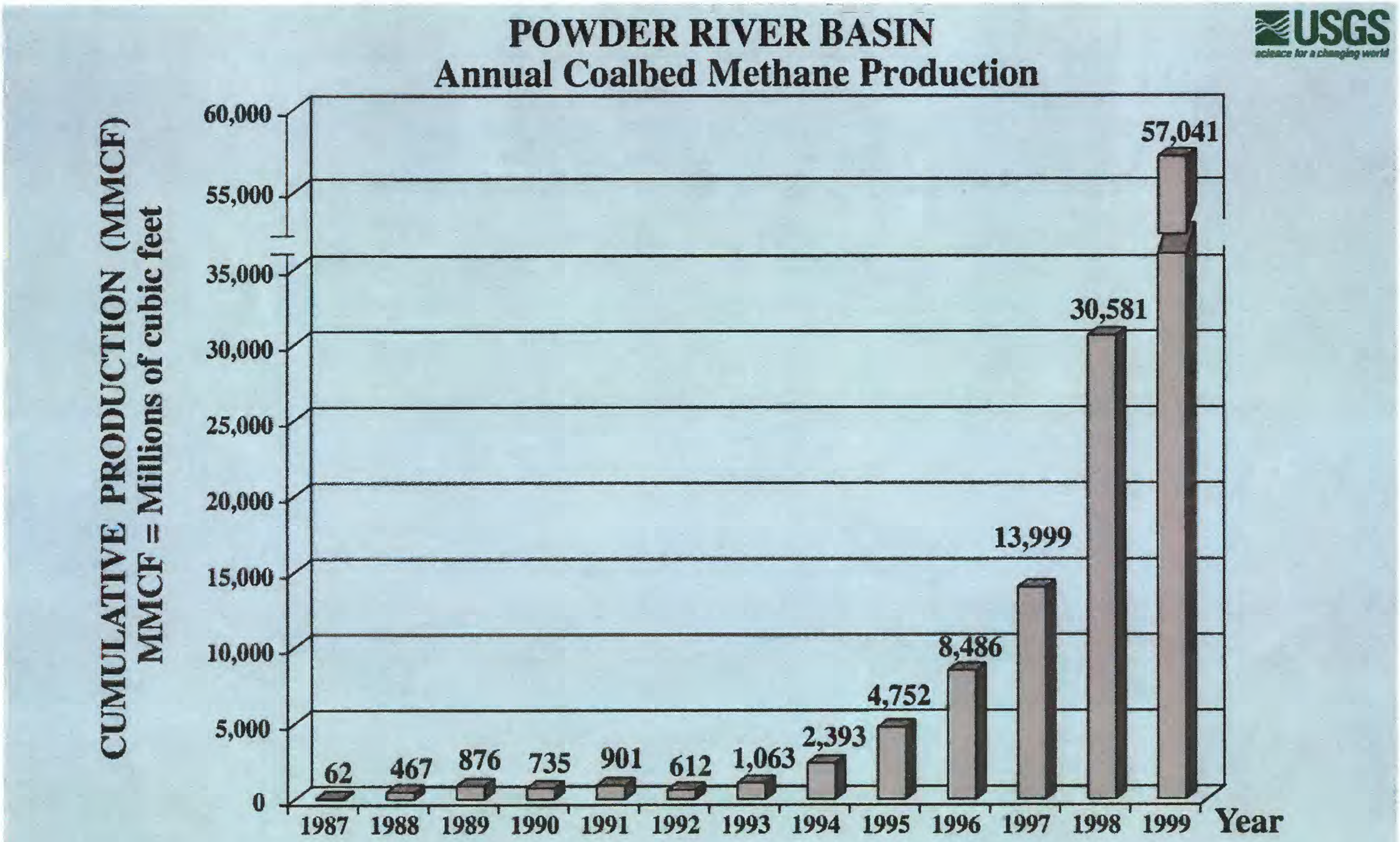

POWDER RIVER BASIN
Annual Coalbed Methane Production
CUMULATIVE PRODUCTION (MMCF)
MMCF = Millions of cubic feet
60,000
55,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
62
467
876
735
901
612
1,063
2,393
4,752
8,486
13,999
30,581
57,041
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
Year
USGS
science for a changing world

Figure 42

USGS
science for a changing world

BIOGENIC GAS

$\delta^{13}C$ Values in the range of -55 to -110‰

Isotopically Light

GAS STORAGE

Gas is retained by molecular attraction on internal coal surfaces (e.g., cleats, fractures, and pores)

$\delta^{13}C = \delta^{13}$ Carbon Isotope

Figure 43


USGS
canister
Canister seal
(4 inch gripper plug)
Gas release
valve
C3
Quick release
coupling
Thermal
probe opening

Figure 44

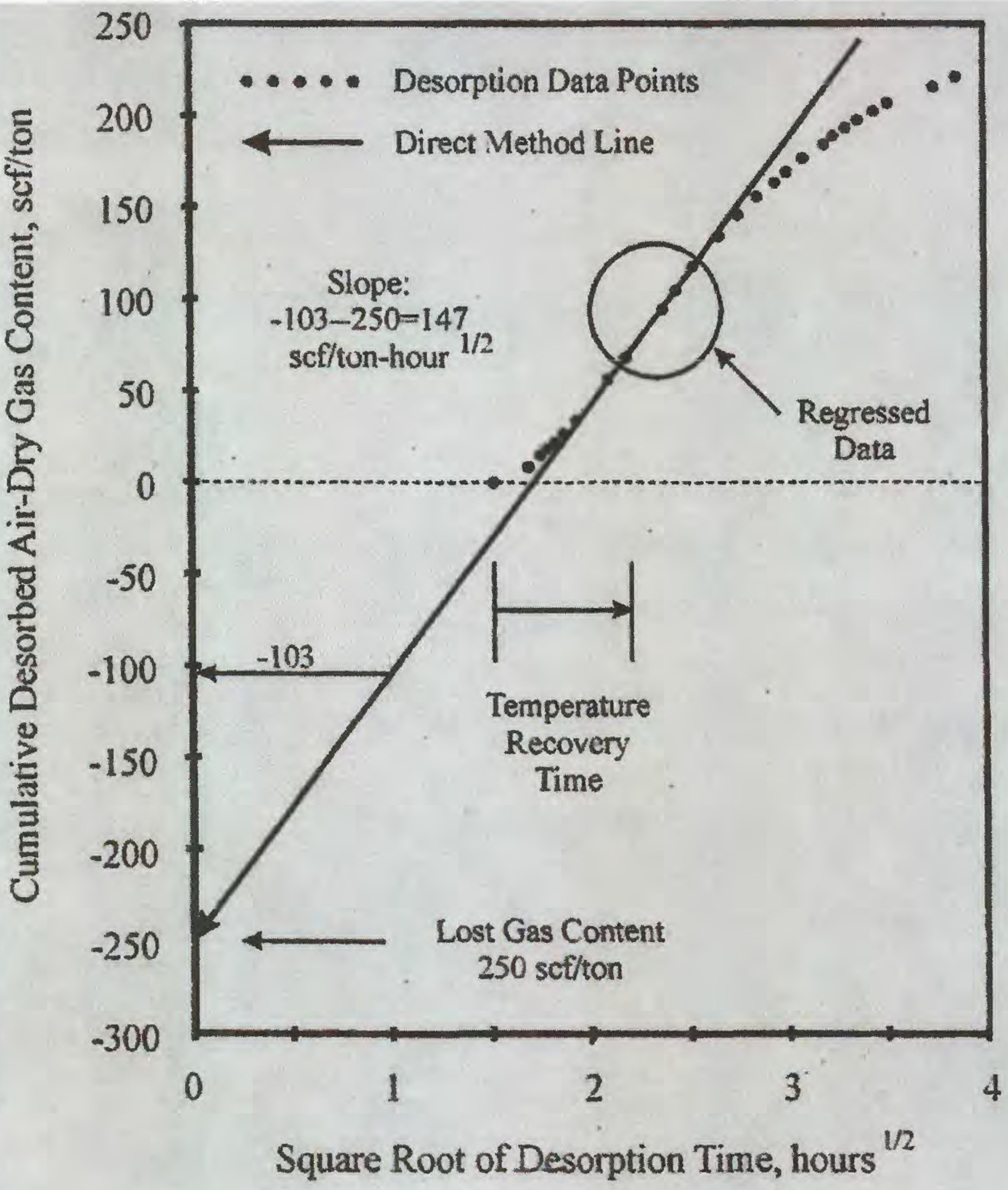
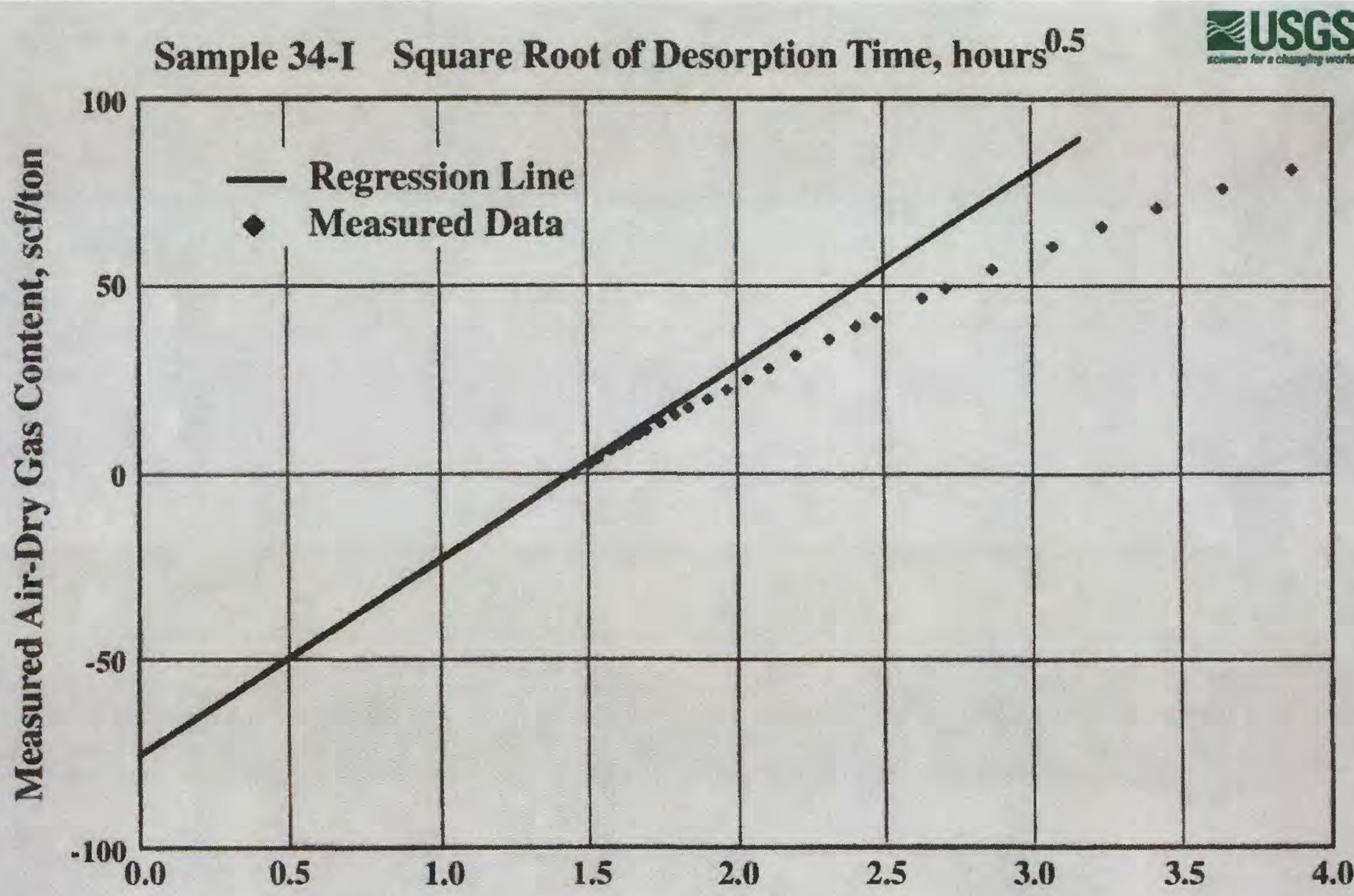


Figure 45

USGS
science for a changing world

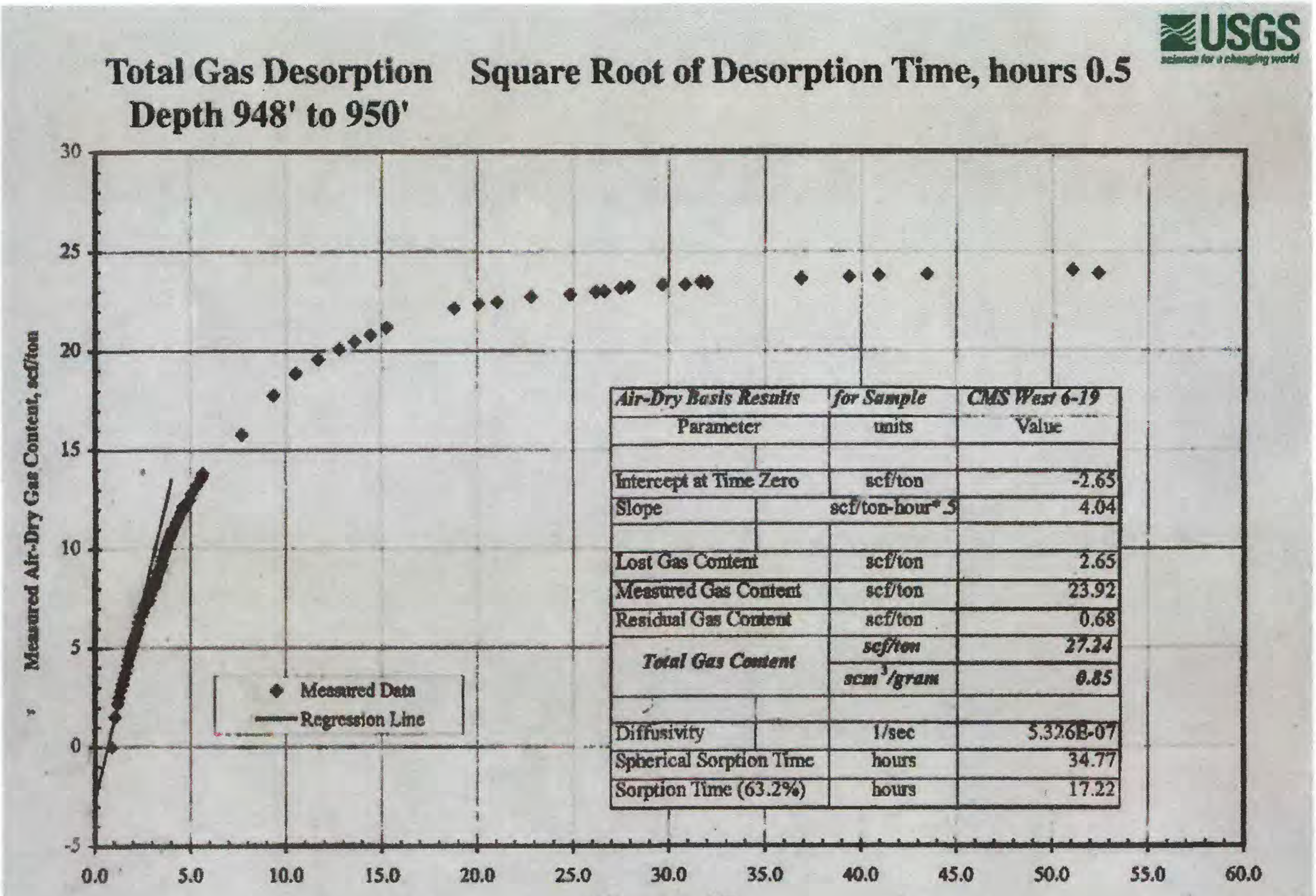


Sample 34-I Square Root of Desorption Time, hours^0.5
Regression Line
Measured Data
Measured Air-Dry Gas Content, scf/ton
100
50
0
-50
-100
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Figure 46

Total Gas Desorption **Square Root of Desorption Time, hours 0.5**

Depth 948' to 950'



Air-Dry Basis Results	*for Sample*	*CMS West 6-19*
Parameter	units	Value
Intercept at Time Zero	scf/ton	-2.65
Slope	scf/ton-hour^.5	4.04
Lost Gas Content	scf/ton	2.65
Measured Gas Content	scf/ton	23.92
Residual Gas Content	scf/ton	0.68
Total Gas Content	***scf/ton***	***27.24***
	scm^3/gram	***0.85***
Diffusivity	1/sec	5.326E-07
Spherical Sorption Time	hours	34.77
Sorption Time (63.2%)	hours	17.22

Figure 47

USGS
science for a changing world

Table 1. Coal resource calculations reported by county, overburden thickness, coal thickness, and reliability categories as determined from overburden thickness. Modified from Ellis and others (1999b)

County	Overburden thickness	Net coal thickness	Reliability categories (distance from data point)				Grand total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
CAMPBELL	0-100 ft	2.5-5 ft	0.94	6.5	2.1	0.099	9.6
		5-10 ft	4.7	23	10	0.45	39
		10-20 ft	32	100	50	0.74	190
		20-30 ft	48	110	80	0	240
		30-40 ft	95	320	180	0	600
		40-50 ft	190	690	360	140	1,400
		50-100 ft	570	1,800	1,800	280	4,400
		100-150 ft	190	240	56	0	480
		150-200 ft	0	5.1	0	0	5.1
	0-100 ft total		1,100	3,300	2,500	420	7,400
	100-200 ft	2.5-5 ft	0.11	0.43	0.11	0	0.65
		5-10 ft	0.58	0.96	1.6	0	3.1
		10-20 ft	4.8	14	6.4	0	25
		20-30 ft	2.8	28	15	0	46
		30-40 ft	24	110	27	0	160
		40-50 ft	100	460	86	0	650
		50-100 ft	880	2,600	950	0	4,500
		100-150 ft	380	660	5.8	0	1,000
		150-200 ft	28	56	0	0	84
	100-200 ft total		1,400	4,000	1,100	0	6,500

MST = Millions of short tons

Table 2. Coal resource calculations by reliability categories as determined from overburden thickness (200-500 ft) and coal thickness (10-200, 5-200 ft). Modified from Ellis and others (1999b)

County	Overburden thickness	Net coal thickness	Reliability categories (distance from data point)				Grand total (MST)
			Measured (<1/4 mi)	Indicated (1/4-3/4 mi)	Inferred (3/4-3 mi)	Hypothetical (>3 mi)	
CAMPBELL	200-300 ft	10-20 ft	2.5	0.97	0	0	3.5
		20-30 ft	2.9	25	2.8	0	31
		30-40 ft	5.7	78	27	0	110
		40-50 ft	84	390	130	0	600
		50-100 ft	1,300	4,500	1,100	0	6,900
		100-150 ft	510	860	88	0	1,500
		150-200 ft	0	11	0	0	11
	200-300 ft total		1,900	5,800	1,400	0	9,100
	300-400 ft	5-10 ft	0.16	0.21	0	0	0.37
		10-20 ft	1.3	4.9	18	0	25
		20-30 ft	1.0	3.8	50	0	55
		30-40 ft	9.4	10	96	0	120
		40-50 ft	48	170	80	0	300
		50-100 ft	1,600	5,300	1,700	0	8,600
		100-150 ft	380	1,000	270	0	1,700
		150-200 ft	11	20	0	0	31
	300-400 ft total		2,100	6,500	2,200	0	11,000
	400-500 ft	5-10 ft	0.6	4.0	3.9	0	8.4
		10-20 ft	0.72	2.2	5.3	0	8.3
		20-30 ft	1.4	6.9	0.97	0	9.3
		30-40 ft	4.7	22	32	2.0	61
		40-50 ft	7.0	19	100	17	150
		50-100 ft	1,400	4,600	2,800	0	8,800
		100-150 ft	610	1,600	390	0	2,600
		150-200 ft	3.0	11	0	0	14
	400-500 ft total		2,000	6,300	3,400	19	12,000

MST = Millions of short tons

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Table 3. Coal resources reported by county and 7.5-minute quadrangle map area. Modified from Ellis and others (1999b)

County	7.5-minute quadrangle map	Total (MST)	County	7.5-minute quadrangle map	Total (MST)
CAMPBELL	APPEL BUTTE	5,000	CAMPBELL	PLEASANTDALE	2,900
	BAKER SPRING	1,900		RATTLESNAKE DRAW	4,000
	BETTY RESERVOIR	110		RAWHIDE SCHOOL	4,300
	CALF CREEK	1,000		RENO FLATS	4,300
	COAL BANK DRAW	1.0		RENO JUNCTION	6,000
	COAL DRAW NORTH	85		RENO RESERVOIR	3,100
	COON TRACK CREEK	74		ROCKY BUTTE GULCH	6,400
	COYOTE DRAW	1,400		ROUGH CREEK	1,400
	DUGOUT CREEK NORTH	52		SADDLE HORSE BUTTE	390
	EAGLE ROCK	4,200		SCAPER RESERVOIR	5,900
	FORTIN DRAW	370		TECKLA	3,700
	FOUR BAR J RANCH	2,600		TECKLA SW	4,900
	GILLETTE EAST	2,400		THE GAP	3,900
	GILLETTE WEST	5,000		THE GAP SW	3,200
	GREASEWOOD RESERVOIR	2,100		THREEMILE CREEK RESERVOIR	6,400
	HILIGHT	3,500		TURNERCREST	1,200
	LITTLE THUNDER RESERVOIR	5,800		WESTON SW	55
	MACKEN DRAW	2.9		WILDCAT	590
	MOYER SPRINGS	510	CAMPBELL total		110,000
	NEIL BUTTE	2,200	CONVERSE	BETTY RESERVOIR	1,600
	OPEN A RANCH	450		COAL BANK DRAW	36
	ORIVA	2,900		COAL DRAW NORTH	1,000
	ORIVA NW	3,300		DUGOUT CREEK NORTH	730
	PEPSSON DRAW	2,800		MACKEN DRAW	200
	PINEY CANYON NW	110	CONVERSE total		3,600
	PINEY CANYON SW	500	Grand total (MST)		110,000

MST = Millions of short tons

Table 4. Coal Resources reported by county and Federal ownership. Modified from Ellis and others (1999b)

County	Federal ownership	Total (MST)
CAMPBELL	No Federal coal or Federal surface ownership	9,000
	No Federal coal, but Federal surface ownership	1,900
	Federal coal, but no Federal surface ownership	94,000
	Federal coal and Federal surface ownership	5,900
CAMPBELL total		110,000
CONVERSE	No Federal coal or Federal surface ownership	340
	No Federal coal, but Federal surface ownership	30
	Federal coal, but no Federal surface ownership	2,400
	Federal coal and Federal surface ownership	810
CONVERSE total		3,600
Grand total (MST)		110,000

MST = Millions of short tons

Table 5. Coal resources reported by reliability categories as calculated by statistical and confidence limit parameters. Modified from Ellis and others (1999b)

Parameter	Reliability category				Entire area
	Measured	Indicated	Inferred	Hypothetical	
Area (in square meters)	416,538,074	1,530,925,727	1,602,753,691	60,295,123	3,610,512,615
Percent of area	12	42	44	2	100
Acres (area x 0.0002471)	102,929	378,300	396,049	14,899	892,177
SD (standard deviation (in ft) from semi-variogram model)	19.65	23.33	26.33	26.33	NA
Acre feet (acres x SD)	2,022,084	8,825,319	10,426,851	392,255	NA
Volume standard deviation (MST)	125	854	3,945	694	5,618
Pseudo #n	819	334	22	1	NA

Parameter	Reliability category				Entire area
	Measured	Indicated	Inferred	Hypothetical	
Total calculated resource (MST)	13,520	48,160	51,260	1,597	114,500
Lower 90% confidence limit (MST)	13,310	46,760	44,770	455.0	105,300
Upper 90% confidence limit (MST)	13,730	49,570	57,750	2,739	123,800

SD = Standard deviation

MST = Millions of short tons

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Table 6. The lost gas, desorbed gas, residual gas, and gas content from nine samples of the Big George at drill hole B23-BG1CB. Adapted from Boreck and Weaver (1984) ft (feet); gm (gram); cc (cubic centimeters); scft (standard cubic feet per ton).

Sample	Depth (ft)	Thickness (ft)	Weight (gm)	Lost Gas (cc)	Desorbed Gas (cc)	Residual Gas (cc / gm)	Total Gas (cc / gm)	Total Gas Content (scf / t)
MRBG1	1052.25-1053.10	0.85	1220	340	2027	0	1.94	62
MRBG2	1085.20-1085.85	0.65	1563	460	2284	0	1.76	56
MRBG3	1124.35-1125.15	0.80	1458	776	2484	0.07	2.31	74
MRBG4	1166.15-1166.95	0.80	1300	358	2433	0	2.15	69
MRBG5	1178.40-1179.40	1.0	1196	438	1873	0.045	1.98	63
MRBG6	1195.26-1196.05	0.08	1516	334	2494	0	1.87	60
MRBG7	1225.25-1226.05	0.08	1362	375	2293	0	1.96	63

Table 7. The gas contents in scft/t (standard cubic feet per ton) for the Anderson coals in wells drilled by USGS, Betop, Exxon.

Well	Number of samples	Scf/ton
USGS "Big George"	7	56-74
Betop Dead Horse Creek 8 - 12	3	26 - 44
Exxon #2 Robert C. Harper "B"	3	44
Exxon #1 Shogrin Federal	15	29
Exxon #2 Shogrin Federal	4	6 - 12

Table 8. Chemical composition of coalbed methane from the "Big George" coal. Modified from Boreck and Weaver (1984)

Sample	Type	N_2 nitrogen	CO_2 carbon dioxide	C_1 methane	C_2 ethane	C_3 propane	iC_4 isobutane	nC_4 normal butane	iC_5 isopentane	nC_5 normal pentane	dc^{13} 0/00	C_1/C_{1-5}
MRBG2	Canister	37.84	4.84	57.08	0.22	0.025	------	------	------	------	------	------
	air-free	-------	7.79	91.81	0.35	0.04	------	------	------	------	-58.64	0.9958
MRBG3	Canister	31.95	3.93	63..71	0.29	0.04	0.01	0.06	------	------	------	------
	air-free	------	5.78	93.63	0.43	0.06	0.02	0.08	------	------	-59.29	0.9936
MRBG4	Canister	34.23	6.17	59.08	0.30	0.10	0.03	0.02	0.06	0.005	------	------
	air-free	-------	9.38	89.83	0.45	0.15	0.05	0.03	0.10	0.01	-60.07	0.9913
MRBG5	Canister	44.42	3.90	51.45	0.14	0.09	------	------	------	------	------	------
	air-free	-------	7.01	92.57	0.26	0.16	------	------	------	------	-59.98	0.9955
MRBG6	Canister	43.43	6.07	50.03	0.33	0.13	0.01	------	------	------	------	------
	air-free	-------	10.72	88.44	0.59	0.22	0.02	------	------	------	-60.85	0.9907
MRBG7	Canister	67.27	1.31	30.45	0.17	0.19	0.32	0.08	0.19	0.01	------	------
	air-free	-------	4.00	93.04	0.53	0.58	0.97	0.24	0.59	0.04	-53.59	0.9691

Well Identification	
Well Name	GRI Observation Well #2
Operator	Amoco Production Co.
County	La Plata County
State	Colorado
Section	S. 17, T32N, R11W
Field	Ignacio Blanco

Canister Data		
Canister No.		14-29
Empty Weight	g	4,135
Filled Weight	g	5,915
Empty Volume	cc	3,035
Headspace Volume	cc	1,143

Core Run Identification		
Formation		Fruitland
Coal Interval		Basal
Core Run #		1
Sample Top Depth	feet	3,163.0
Sample Bottom Depth	feet	3,164.0
Coring Fluid Density	ppg	10.5

Sample Data		
Sample ID No.		36-7
Air-Dry Weight	g	1,698
Sample Volume	cc	1,892
Ash Content	fraction	0.2481
Moisture Content	fraction	0.1141
Residual Gas Content	scf/ton	0.00

Reservoir Data		
Temperature	Deg. F	120
Pressure Gradient	psi/ft	0.479

Misc. Information

Pressure at standard conditions: 30.01 in Hg

Temperature at standard conditions: 60 Deg. F.

Recovery Times	
Time when the top of the sample was cored	01/17/91 04:10:00
Time when the core barrel started out of the well	01/17/91 07:10:00
Time when the core barrel reached surface	01/17/91 09:25:00
Time when the sample canister was sealed	01/17/91 09:45:00
Time at time zero	01/17/91 07:26:34
Time at measurement start	01/17/91 10:13:00

Interpretation Parameters		
Reservoir Pressure	psia	1,526.87
Fluid Hydrostatic Pressure	psia	1,738.83
Temp. Recovery Time	hours	2.583
Des. Time Correction	hours	0.467
End of Temp. Recovery	hours*0.5	2.103
Start of Regression	hours*0.5	2.200
End of Regression	hours*0.5	2.400

Time			Uncorrected Data		Measurement Conditions			Corrected Data	
Date & Time	Desorption Time	Square Root of Desorption Time	Incremental Desorbed Volume	Desorbed Volume	Canister Temperature	Ambient Temperature	Ambient Pressure	Cumulative Desorbed Volume	Cumulative Desorbed Gas Content
mm/dd/yy hh:mm:ss	hours	hours*0.5	cc	cc	Deg. F	Deg. F	Inches Hg	cc @ STP	scf/ton
01/17/91 09:45:00	1.841	1.357	0	0	40	40	23.59	0	0
01/17/91 10:13:00	2.307	1.519	760	760	120	75	23.59	452	8.52
01/17/91 10:24:00	2.491	1.578	395	1,155	120	75	23.59	753	14.22
01/17/91 10:29:00	2.574	1.604	220	1,375	120	75	23.59	922	17.39
01/17/91 10:37:00	2.707	1.645	310	1,685	120	75	23.59	1,158	21.86
01/17/91 10:45:00	2.841	1.685	310	1,995	120	75	23.59	1,395	26.32
01/17/91 10:58:00	3.057	1.748	520	2,515	120	75	23.59	1,793	33.82
01/17/91 11:32:00	3.624	1.904	1,545	4,060	120	75	23.55	2,970	56.03
01/17/91 11:52:00	3.957	1.989	825	4,885	122	75	23.53	3,595	67.83
01/17/91 12:37:00	4.707	2.170	1,825	6,710	122	75	23.53	4,986	94.07
01/17/91 12:55:00	5.007	2.238	730	7,440	122	75	23.51	5,541	104.54
01/17/91 13:18:00	5.391	2.322	925	8,365	122	75	23.51	6,245	117.83
01/17/91 13:56:00	6.024	2.454	1,120	9,485	122	75	23.51	7,098	133.92
01/17/91 14:25:00	6.507	2.551	780	10,265	122	75	23.48	7,690	145.09
01/17/91 14:55:00	7.007	2.647	715	10,980	122	75	23.48	8,234	155.35
04/09/91 07:37:00	1,967.707	44.359	60	22,882	122	75	25.26	17,477	329.74
04/10/91 07:37:00	1,991.707	44.629	25	22,907	128	75	24.85	17,474	329.70
04/11/91 07:44:00	2,015.824	44.898	0	22,907	125	75	24.81	17,477	329.75
04/12/91 07:43:00	2,039.807	45.164	0	22,907	124	75	24.93	17,483	329.86
04/15/91 07:34:00	2,111.657	45.953	20	22,927	120	75	24.84	17,502	330.21
04/16/91 07:36:00	2,135.691	46.214	158	23,085	121	75	24.82	17,627	332.57
04/17/91 07:49:00	2,159.907	46.475	0	23,085	122	75	24.91	17,628	332.60

Table 9. Example of core desorption data sheet

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Well Identification	
Well Name	Valencia Canyon 32-1
Operator	Bowen & Edwards
County	La Plata County
State	Colorado
Section	Sec. 32 T33N R11W
Field	Valencia Canyon

Canister Data		
Canister No.		12-44
Empty Weight	g	4,140
Filled Weight	g	6,349
Empty Volume	cc	2,403
Headspace Volume	cc	889

Core Run Identification		
Formation		Fruitland
Coal Interval		Intermediate
Core Run #		2
Sample Top Depth	feet	1,774.0
Sample Bottom Depth	feet	1,774.8
Coring Fluid Density	ppg	10.2

Sample Data		
Sample ID No.		34-1
Air-Dry Weight	g	2,127
Sample Volume	cc	1,514
Ash Content	fraction	0.4845
Moisture Content	fraction	0.0696
Residual Gas Content	scf/ton	0.00

Reservoir Data		
Temperature	Deg. F	100
Pressure Gradient	psi/ft	0.526

Misc. Information

Pressure at standard conditions: 30.01 in Hg

Temperature at standard conditions: 60 Deg. F.

Interpretation Parameters		
Reservoir Pressure	psia	
Fluid Hydrostatic Pressure	psia	
Temp. Recovery Time	hours	
Des. Time Correction	hours	
End of Temp. Recovery	hours*0.5	
Start of Regression	hours*0.5	
End of Regression	hours*0.5	

Recovery Times	
Time when the top of the sample was cored	11/23/90 13:47:00
Time when the core barrel started out of the well	11/23/90 14:44:00
Time when the core barrel reached surface	11/23/90 16:45:00
Time when the sample canister was sealed	11/23/90 17:01:08
Time at time zero	
Time at measurement start	

Time			Uncorrected Data		Measurement Conditions			Corrected Data	
Date & Time	Desorption Time	Square Root of Desorption Time	Incremental Desorbed Volume	Desorbed Volume	Canister Temperature	Ambient Temperature	Ambient Pressure	Cumulative Desorbed Volume	Cumulative Desorbed Gas Content
mm/dd/yy hh:mm:ss	hours	hours*0.5	cc	cc	Deg. F	Deg. F	Inches Hg	cc @ STP	scf/ton
11/23/90 17:01:08			0	0	25	25	23.93		
11/23/90 17:11:00			340	340	91	75	23.93		
11/23/90 17:16:00			130	470	91	75	23.93		
11/23/90 17:24:00			185	655	91	75	23.93		
11/23/90 17:30:00			115	770	91	75	23.93		
11/23/90 17:36:00			115	885	91	75	23.93		
11/23/90 17:42:00			120	1,005	91	75	23.93		
11/23/90 17:48:00			110	1,115	91	75	23.93		
11/23/90 17:58:00			160	1,275	88	75	23.93		
11/23/90 18:08:00			180	1,455	88	75	23.93		
11/23/90 18:18:00			165	1,620	88	75	23.93		
11/23/90 18:32:00			200	1,820	88	75	23.93		
11/23/90 18:47:00			220	2,040	88	75	23.93		
11/23/90 19:04:00			230	2,270	88	75	23.93		
11/23/90 19:22:00			255	2,525	90	75	23.93		
11/23/90 19:46:00			295	2,820	90	75	23.93		
11/23/90 20:17:00			370	3,190	90	75	23.93		
11/23/90 20:42:00			290	3,480	90	75	23.93		
11/23/90 21:02:00			220	3,700	89	75	23.93		
11/23/90 21:50:00			430	4,130	89	75	23.93		
11/23/90 22:15:00			240	4,370	88	75	23.93		

Table 10. Core Desorption Data Sheet

Well Identification			Canister Data		
Well Name	Valencia Canyon 32-1		Canister No.		12-44
Operator	Bowen & Edwards		Empty Weight	g	4,140
County	La Plata County		Filled Weight	g	6,349
State	Colorado		Empty Volume	cc	2,403
Section	Sec. 32 T33N R11W		Headspace Volume	cc	889
Field	Valencia Canyon		**Sample Data**		
Core Run Identification			Sample ID No.		34-1
Formation		Fruitland	Air-Dry Weight	g	2,127
Coal Interval		Intermediate	Sample Volume	cc	1,514
Core Run #		2	Ash Content	fraction	0.4845
Sample Top Depth	feet	1,774.0	Moisture Content	fraction	0.0696
Sample Bottom Depth	feet	1,774.8	Residual Gas Content	scf/ton	0.00
Coring Fluid Density	ppg	10.2	**Misc. Information**		
Reservoir Data			Pressure at standard conditions: 30.01 in Hg		
Temperature	Deg. F	100	Temperature at standard conditions: 60 Deg. F.		
Pressure Gradient	psi/ft	0.526			

Recovery Times		Interpretation Parameters		
Time when the top of the sample was cored	11/23/90 13:47:00	Reservoir Pressure	psia	945.50
Time when the core barrel started out of the well	11/23/90 14:44:00	Fluid Hydrostatic Pressure	psia	952.86
Time when the core barrel reached surface	11/23/90 16:45:00	Temp. Recovery Time	hours	2.286
Time when the sample canister was sealed	11/23/90 17:01:08	Des. Time Correction	hours	0.164
Time at time zero	11/23/90 14:44:56	End of Temp. Recovery	hours*0.5	2.095
Time at measurement start	11/23/90 17:11:00	Start of Regression	hours*0.5	
		End of Regression	hours*0.5	

Time			Uncorrected Data		Measurement Conditions			Corrected Data	
Date & Time	Desorption Time	Square Root of Desorption Time	Incremental Desorbed Volume	Desorbed Volume	Canister Temperature	Ambient Temperature	Ambient Pressure	Cumulative Desorbed Volume	Cumulative Desorbed Gas Content
mm/dd/yy hh:mm:ss	hours	hours*0.5	cc	cc	Deg. F	Deg. F	Inches Hg	cc @ STP	scf/ton
11/23/90 17:01:08	2.106	1.451	0	0	25	25	23.93	0	0
11/23/90 17:11:00	2.270	1.507	340	340	91	75	23.93	172	2.60
11/23/90 17:16:00	2.353	1.534	130	470	91	75	23.93	273	4.11
11/23/90 17:24:00	2.487	1.577	185	655	91	75	23.93	417	6.27
11/23/90 17:30:00	2.587	1.608	115	770	91	75	23.93	506	7.62
11/23/90 17:36:00	2.687	1.639	115	883	91	75	23.93	595	8.96
11/23/90 17:42:00	2.787	1.669	120	1,005	91	75	23.93	688	10.36
11/23/90 17:48:00	2.887	1.669	110	1,115	91	75	23.93	773	11.64
11/23/90 17:58:00	3.053	1.747	160	1,275	88	75	23.93	901	13.57
11/23/90 18:08:00	3.220	1.794	180	1,455	88	75	23.93	1,040	15.67
11/23/90 18:18:00	3.387	1.840	165	1,620	88	75	23.93	1,168	17.59
11/23/90 18:32:00	3.620	1.903	200	1,820	88	75	23.93	1,323	19.93
11/23/90 18:47:00	3.870	1.967	220	2,040	88	75	23.93	1,494	22.50
11/23/90 19:04:00	4.153	2.038	230	2,270	88	75	23.93	1,672	25.18
11/23/90 19:22:00	4.453	2.110	255	2,525	90	75	23.93	1,867	28.12
11/23/90 19:46:00	4.853	2.203	295	2,820	90	75	23.93	2,096	31.57
11/23/90 20:17:00	5.370	2.317	370	3,190	90	75	23.93	2,382	35.88
11/23/90 20:42:00	5.787	2.406	290	3,480	90	75	23.93	2,607	39.27
11/23/90 21:02:00	6.120	2.474	220	3,700	89	75	23.93	2,779	41.86
11/23/90 21:50:00	6.920	2.631	430	4,130	89	75	23.93	3,112	46.88
11/23/90 22:15:00	7.337	2.709	240	4,370	88	75	23.93	3,299	49.70
	1,121.387	33.487		13,297				10,147	152.83

Table 11. Coal desorption data sheet

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