COAL GEOLOGY AND RESOURCES

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Summary

Coal is the most abundant fossil fuel resource currently used in the world and is expected to be a vital component of the world's energy resources for the foreseeable future. This article, written for a general audience, provides a review of the science of coal geology, describes how coal was formed, and discusses the various methods of characterizing the energy resource. Finally a discussion of the various uses of coal is presented.

Coal may be characterized by considering the evolutional process that takes coal from its origin to its eventual use as a resource. The study of coal geology incorporates an understanding of coal formation, coal extraction and utilization, coal quality and environmental considerations, and coal as a source rock for liquid and gaseous hydrocarbons. Coal geology is concerned with the study of the geologic factors that control the generation and thermal maturation of coal and its overall quality as a fuel, its potential to generate and store hydrocarbons (such as methane), and with the factors that control the environmentally important impurities within the coal bed. In this article, a brief discussion is presented for the various components of coal geology. The components include: climate, eustacy, tectonics, diagenesis, thermal history, and other factors that control coal formation and distribution. The study of coal geology helps researchers understand the complex nature of the many different types of coal and how the various disciplines of coal geology may be used together to address the environmental problems associated with coal utilization.

1. Introduction to the Coal Geology and the Stages of Coal Development

This summary written for the general reader will provide a review of the science of coal geology, describe how coal was formed, and will discuss the various methods of characterizing the energy resource. Finally a discussion of the uses of coal is presented.
Coal geology has many disciplines that focus on the geologic factors that control the generation and thermal maturation of coal and its overall quality as a fuel, its potential to generate and store hydrocarbons (such as methane), and the factors that control the environmentally important impurities within the coal bed. The various disciplines of coal geology seek a better understanding of the things that influence the formation and distribution of coal beds, such as climate, eustacy, tectonics, diagenesis, thermal history. In an effort to examine the various disciplines of coal geology, this paper uses the stages of coal development (the accumulation phase, the burial and preservation stage, and the diagenesis–coalification stage) as an outline for discussion. In addition, the paper addresses coal characterization techniques, resource issues and coal utilization. The study of coal geology helps scientists understand the complex nature of the many different types of coal and how the various disciplines of coal geology may be used together to address the environmental problems associated with coal utilization.

2. Accumulation Phase - Review of Coal-forming Environments

The following topics (2.1 - 2.4) contain an overview of the preliminary stage of a coal deposit's life, namely the peat accumulation phase.

2.1. Depositional systems: Fluvial, Deltaic, and Other

Peat, the precursor of coal, accumulates in many environments ranging from subarctic marshes to tropical rain forests. In all cases accumulation of organic matter must exceed the oxidation or biodegradation of the organic matter. Most coal deposits were formed in ancient river systems that include river flood plains and deltas. Peat accumulates where the low-lying, moist and flood-prone topography allowed vegetable matter to accumulate through time. Other places that are common depositional environments for peat could include lake fringes and abandoned river channels that fill in with vegetation. Broad, flat wet coastal plains that are protected from wave action and ocean water incursion by beach ridges or barrier islands are also environments where peat deposits might form. Most other fluvial environments, such as those associated with braided rivers and alluvial fans, usually have too much sediment deposition to allow for the accumulation and preservation of large deposits of peat. Modern examples of places where peat is currently accumulating include flood plains of large river systems of the world such as the Mississippi River (USA), the Amazon River (Brazil), behind beach ridges in low-lying swamps such as in the Okefenokee Swamp in Florida (USA), and in coastal and river floodplain environments in Indonesia. Peat also accumulates in high-latitude environments, including northern Ireland, Scotland, and Russia. Peat accumulates in climatic conditions ranging from tropical, warm, to subarctic. In all cases, the peat must be buried and preserved in sediments to eventually form a coal deposit. The process of peat accumulation and transformation into coal generally takes place over many millions of years.

2.2. Coal-forming Plants

Coal is composed of the fossilized remains of plants that range from tropical to subarctic that grew millions of years ago. The vegetable material, including tree trunks, roots, branches, leaves, grass, algae, spores, and a mixture of all plant parts, accumulated in mire environments that were subsequently buried by sediments derived from rivers or seas that ultimately filled in subsiding basins. Through time, the weight of the overlying sediment and inherent temperature in the Earth's crust transformed the organic matter into coal. In addition, hydrocarbons (gas and oil) may be generated during this coalification process.

2.3. Climate, Eustacy, Tectonics

Many factors are important to consider when trying to reconstruct how a particular coal deposit might have been formed. Not only are there chemical and biological processes going on during peat deposition, but the regional climate, the relative position of sea level, and the local geologic setting also strongly influence the shape and form of the peat mire, and ultimately, the coal deposit. Peat requires a wet environment to form, so that the amount of rain a particular location receives will limit or enhance the formation of peat. If an area receives too little rain, and a local sediment source is available, the peat mire may receive too much sediment to allow the accumulation of a large amount of organic matter. If sediment accumulation rates are greater than peat accumulation rates, then shale or mudstone rich in organic material may form instead of peat.

2.4. Syngenetic Processes Affecting the Peat Stage

Syngenetic processes are primarily chemical reactions that occur within the peat-forming environment that affect the overall quality of the resulting coal deposit. An example of a syngenetic process would be the formation of pyrite nodules in the poorly oxidized reducing environments of a peat mire. Other types of secondary minerals such as calcite and quartz can form in this manner.

3. Burial and Preservation

Most of the peat that accumulates is not preserved in the sedimentary rock record because it is eroded by encroaching rivers or seas or is oxidized faster than it is accumulates. The encroachment and erosion usually happens shortly after the peat is deposited. The point at which the peat is preserved in the geologic record is a critical moment in geologic time because the peat can then start its process to become a coal deposit. This idea is very similar to the critical moment in petroleum geology where all the geologic conditions are favorable to allow oil or gas to be preserved in underground geologic traps.

3.1. Basin Subsidence Rate

The rate at which a sedimentary basin subsides will affect the type and amount of peat that can accumulate in the basin. If the basin subsidence rate is low, sediment may rapidly fill the basin and choke the wet, swampy areas that are conducive to peat accumulation. Alternatively, if the basin subsidence rate is too great, freshwater or seawater may inundate the basin and peat deposits may not be able to form. The rate of basin subsidence must be intermediate, not too high or too low, to allow peat to accumulate. If favorable conditions (climate, basin subsidence and peat accumulation rates) persist over broad areas, then thick, widespread coal deposits may form as a result. Examples of deposits formed within ancient, long-lasting, widespread peat-accumulating environments would be the Pittsburgh coal bed, which extends over several Appalachian states, and the Herring coal bed in the Illinois basin, USA.

3.2. Structural Deformation

Once a peat deposit is preserved and coalification begins, folding, faulting, or compaction may deform the strata that contain the peat or coal bed. This deformation can be caused by local or regional stresses in the Earth's crust. Faults may serve as conduits for mineral-rich geothermal fluids to enter the coal bed and cause the deposit to be enriched in undesirable minerals or elements (such as arsenic or mercury). Folding of the coal-bearing strata, if intense enough, can render a coal deposit unminable, or cause mining complications. Compaction is a structural alteration that is always associated with the transition from peat to coal. The amount of compaction varies between coal deposits and is controlled by the original composition of the peat and the depth of burial. For example, low-rank woody coals may not have compacted very much and can be close to the thickness of the original peat deposit, whereas bituminous coals composed of highly degraded organic matter may compact by factors as much as 10:1 or 20:1 from the thickness of the original peat deposit.

3.3. Biogenic Gas Generation

Naturally occurring bacteria in peat or coal can generate significant amounts of methane. Gas generated from the decay of organic matter in the peat stage escapes into the atmosphere and is generally referred to as “swamp gas.” Such biogenic gas generation continues into the coal stages, and if significant amounts of the gas are trapped in the coal or in an adjacent reservoir, such as porous sandstone beds, it may eventually become an economic gas resource. The bacteria thrive on the organic material found in the coal and survive on the nutrients that filter into the coal deposit by groundwater. Many subbituminous coal deposits, such as those of the Powder River basin in Wyoming, owe their coal bed methane resource to the activity of bacteria. The bacteria start the process, known as methanogenesis, in the peat stage. Bacteria production of methane is most pronounced in the peat to subbituminous coal stages, but can continue through to the bituminous and anthracite stages.

4. Diagenesis - Coalification

Coalification is a process by which plant material is altered or metamorphosed to form coal. During this process, elevated temperatures and pressures experienced at depth by the buried deposit geochemically alter the original organic material over an extended period of time. Temperature is the most important of these variables in controlling and driving geochemical alteration and pressure mainly contributes to reduction of coal porosity. The time of application of elevated temperatures and pressures is important in that it may or may not allow the geochemical reaction within a coal bed to proceed to completion. The geochemical alterations that occur during the progressive coalification process include the loss of volatiles (such as methane, carbon dioxide, water, and nitrogen) and the progressive enrichment of organically bound carbon. The various stages along this coalification pathway are as follows:

Peat → Lignite → Subbituminous → Bituminous → Anthracite

The following sections (4.1 - 4.5) give a brief overview of some of the factors that can influence the coalification process.

4.1. Regional Heat Flow

Regional heat flow refers to the amount of geothermal heat that is available in a particular sedimentary basin. Some sedimentary basins have an elevated heat flow due to their proximity to tectonic or igneous activity. Elevated heat flow in sedimentary basins may be associated with deep-seated igneous intrusive bodies. These igneous bodies may generate sufficient temperatures to alter the sediments or sedimentary rocks that enclose the coal bed. Heat flow may also be influenced by the proximity to folding or faulting. For example, deep, hot gasses or liquids may flow upwards through deep-seated basin faults or fractures and heat the rocks adjacent to the faulted or fractured zone or introduce a variety of minerals to the shallower zone.

Rock composition of the sedimentary layers within a basin also influences the thermal conductivity of the sediments. Salt and other evaporites have higher thermal conductivity than do sandstone or claystone.

4.2. Depth of Burial

Usually the degree of coalification, or rank, of a particular coal deposit depends on the maximum temperature to which the coal was exposed during its geologic history. In general, coals buried at great depths have been subjected to greater heat than those coals that have been buried only at shallow depths. Coal beds buried at greater depths will have higher ranks than those preserved at shallower depths. This relationship is known as Hilt's Rule. The average geothermal gradient in the Earth's crust is about 25^{0}C per 1000 m depth. The temperatures necessary to form bituminous coals are usually no higher than 100-150^{0}C, so coal can serve as an important tool to indicate paleo-heat flow within a basin. This fact is also important in hydrocarbon exploration, because oil and natural gas generation depend on the sediments reaching a certain temperature to generate hydrocarbon formation.

4.3. Cleat and Fracture Formation

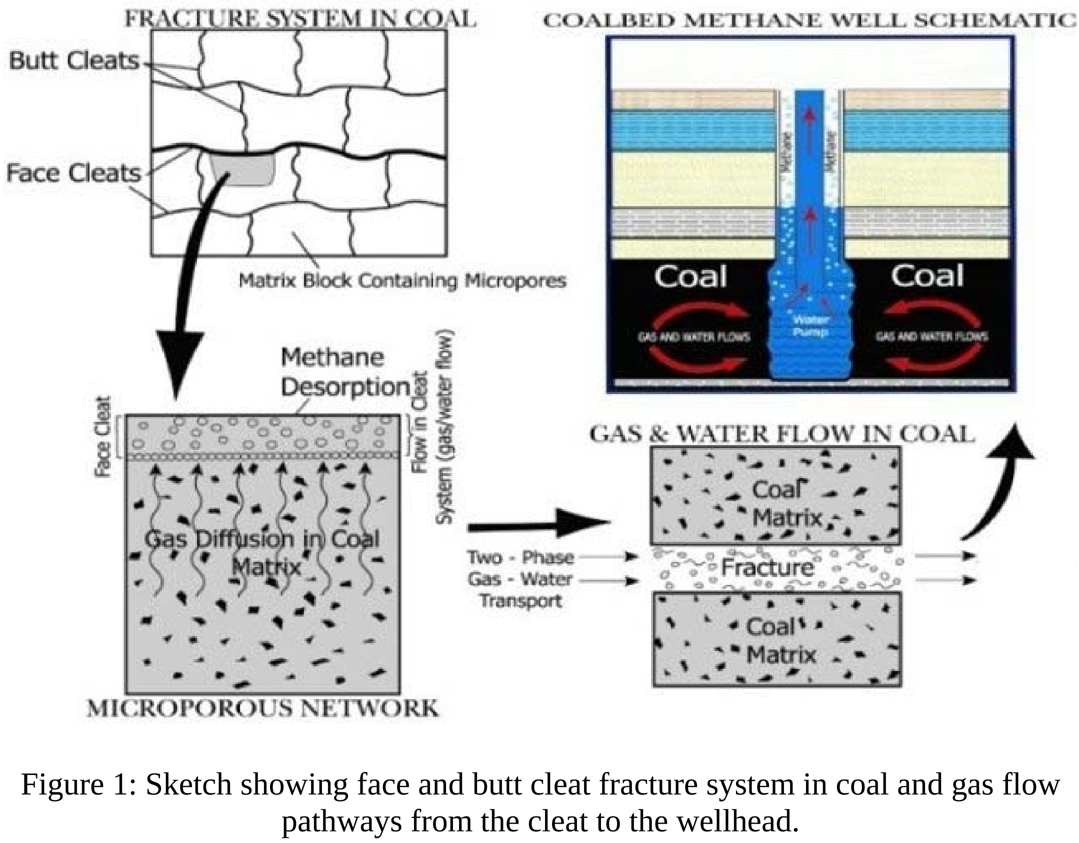

Figure 1: Sketch showing face and butt cleat fracture system in coal and gas flow pathways from the cleat to the wellhead.
From: U.S. Geological Survey Open File Report 01-235 (2001): http://energy.cr.usgs.gov/OF01-235/files/talk%20slides/flores.pdf

Natural fractures in coal are very important features that must be considered in coal mining and in coal-gas production. A fractured or cleated coal may be more easily mined than a non-cleated coal. In coal bed methane applications, coal gas has to be able to move though the coal bed to the borehole to allow gas to flow to the surface. Without the natural fracture system, coal gas could not be produced with current technologies. Cleats generally form a rectilinear sets of fractures referred to as face (dominant) and butt (subordinate) cleats (Figure 1). Cleats and fractures are controlled by bed thickness, coal quality, rank, and most importantly, tectonic deformation and stress. Coal compaction and water loss may also contribute to cleat and fracture formation. The factors which control the ability of water or gas to move through the coal cleat system are cleat (or fracture) frequency, connectivity, and fracture width.

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Recommended Websites

http://energy.usgs.gov/ [A U.S. Geological Survey website with links to many energy-related reports, especially several assessments of undiscovered petroleum resources in the U.S. and around the world]

http://www.uky.edu/KGS/coal/webcoal/coalweb.htm [Kentucky Geological Survey, Coal website]

http://www.newcastle.edu.au/discipline/geology/cfkd/undp.htm [Coal: an introduction by Larissa Gammidge, University of Newcastle, Australia]

http://www.newcastle.edu.au/discipline/geology/cfkd/macerals.htm [Atlas of coal macerals by Larissa Gammidge, University of Newcastle, Australia]

http://mccoy.lib.siu.edu/projects/crelling2/atlas [Petrographic Atlas of coals, cokes, chars, carbons, & graphites, by Professor John C. Crelling, Coal Research Center & Department of Geology. Southern Illinois University, Carbondale, Illinois, 62901, USA.

http://www.worldenergy.org/wec-geis/ [World Energy Council, for world energy resource and production statistics]

http://www.iea.org/ [International Energy Agency, for world energy information]

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http://www.wci-coal.com [World Coal Institute, for data on coal use]

Biographical Sketch

Peter Warwick has a M.S. in Geology from North Carolina State University (1982) and a Ph.D. in Geology from the University of Kentucky (1985). His scientific and technical specialties include sedimentology, stratigraphy, coal and petroleum geology, organic petrology and geochemistry, field geology, and geographic information systems. He was a teacher for several years and a Postdoctoral Research Associate at the National Research Council and the U.S. Geological Survey (USGS). Currently he is employed by the USGS as a research geologist in the Energy Program. His experience includes coal- and gas-related research, exploration, and resource assessments in the Gulf Coast of Mexico Coastal Plain and various western U.S. sedimentary basins. Internationally he has worked in the coal- and gas-bearing basins of Armenia, Bangladesh, Chile, China, India, Pakistan, Poland, and South Korea. He is a member of the USGS World Energy Team for South Asia. His current research focus is on coal geology and coal bed methane resources of the U.S. and the world. He is a member of the American Association of Petroleum Geologists, Geological Society of America (Chair of the Coal Geology Division, 2002), Society for Sedimentary Geology (SEPM), The Society of Organic Petrology (Treasurer/Secretary and Membership Committee Chair, 1998-2002), Geological Society of Washington, and serves on the editorial board of the *International Journal of Coal Geology*.