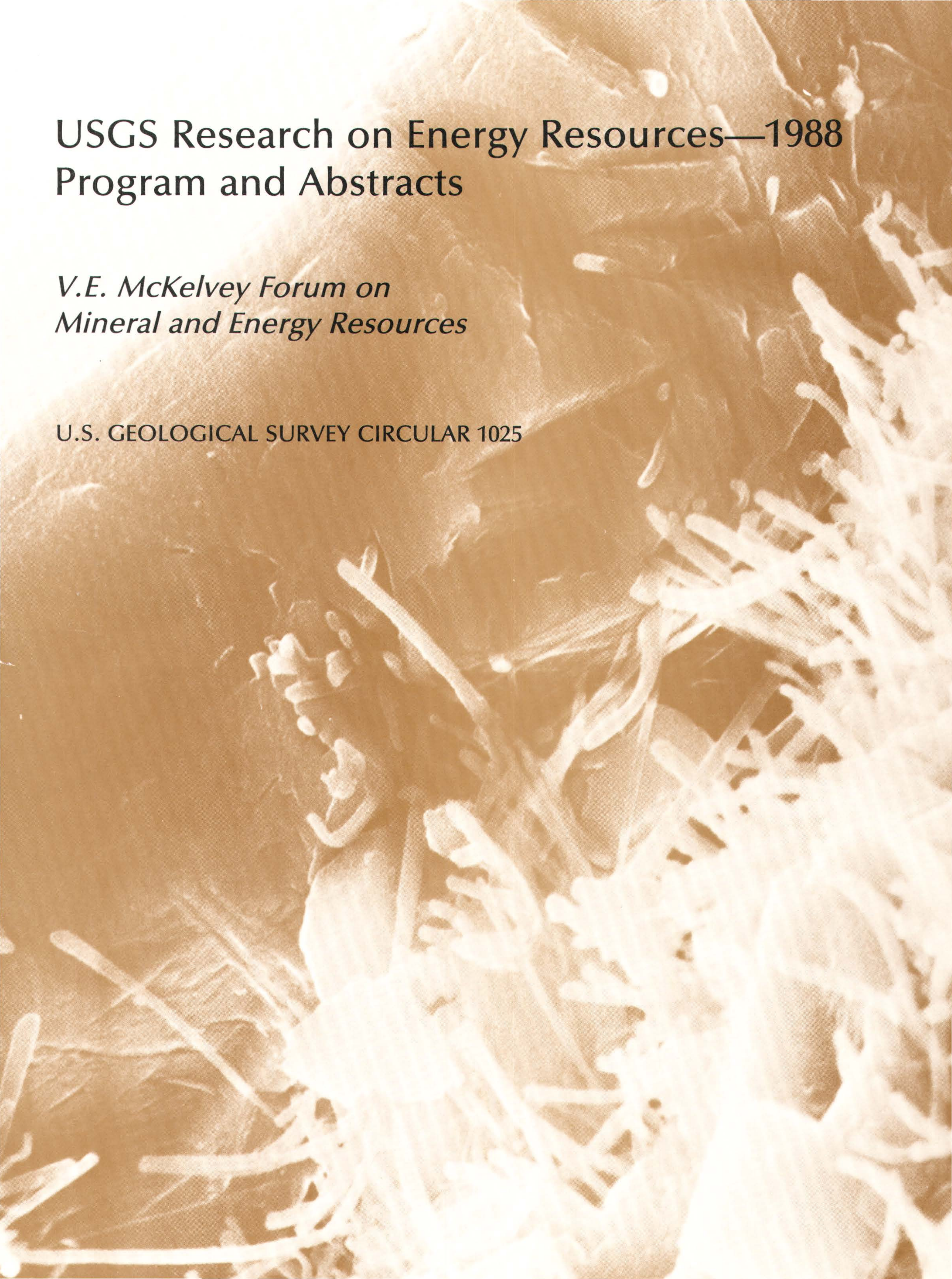
USGS Research on Energy Resources—1988
Program and Abstracts

V.E. McKelvey Forum on
Mineral and Energy Resources

U.S. GEOLOGICAL SURVEY CIRCULAR 1025



Cover.—Scanning electron microscope photograph of authigenic albite and illitic mixed-layer clay (fibrous material) from saline, alkaline playa-lake deposits in the Brushy Basin Member of the Morrison Formation, near Durango, Colorado. The albite, present as a large overgrowth on a detrital feldspar, typically envelops the earlier formed illitic clay. Both authigenic albite and illitic mixed-layer clay have previously been used as geothermometers to assess the thermal history of potential hydrocarbon-bearing sequences; however, petrographic and geologic evidence suggests that pore-water chemistry alone, in the absence of elevated temperatures, controlled formation of these two minerals in the lacustrine units of the Brushy Basin Member. Photo by Neil S. Fishman; field of view is approximately 15 micrometers across.

Title page.—Commercial value of coal is determined to a large extent by circumstances of peat deposition and by conditions of diagenesis in the peat stage. In the process of degrading plant material, bacteria may produce a relatively high content of undesirable iron sulfides—the bright pyrite clumps (framboids) in this photo—which decrease coal value. Degradation by fungi, on the other hand, may lead to formation of resistant fungal cysts (sclerotinite)—the symmetrical chambered bodies. The thermally inert sclerotinite contributes to good strength and high coal value if the coal is used to make metallurgical coke. The layered gray matrix in this Eocene coal from California is highly degraded wood products mixed with plant microspores (faint dark flecks). Photo by Neely Bostick; field approximately 0.15×0.22 mm, polished surface, water immersion optics.

United States Department of the Interior

Geological Survey
Reston, VA 22092

Minerals Management Service
Washington, D.C. 20240

February 26, 1988

Dear Reader:

The U.S. Geological Survey (USGS) and Minerals Management Service (MMS) are nearing completion of a 2-year effort to assess the undiscovered oil and gas resources of the Nation. This investigation utilizes methodologies, assumptions, and data sets that are different than those used in previous assessments by the Department of the Interior.

This year's McKelvey Forum affords us the opportunity in the paper to be presented by Richard Mast to discuss our new approach to the difficult task of assessing undiscovered resources, and to present the preliminary basin results.

In early April, the Department will release a working paper which will describe the details of the methodology, geologic, economic, and engineering assumptions, and preliminary petroleum basin assessments. The USGS and MMS will solicit formal and informal review of the methods and assumptions used in developing the working paper. The review process will include elements of the following:

- Formal review by such organizations as National Academy of Sciences (Board on Mineral and Energy Resources), National Petroleum Council, and Association of American State Geologists.

- Presentation of papers on methodology, assumptions, and results at meetings such as the McKelvey Forum and other professional conferences.

- Regional workshops/conferences involving other Federal agencies, States, industry, and interested organizations.

Your views and opinions on the procedures, assumptions, and preliminary results presented in the working paper will be valuable in assisting the USGS and MMS in preparing a national assessment that would be widely understood and accepted as an accurate appraisal of this Nation's undiscovered oil and gas resources.

Sincerely yours,

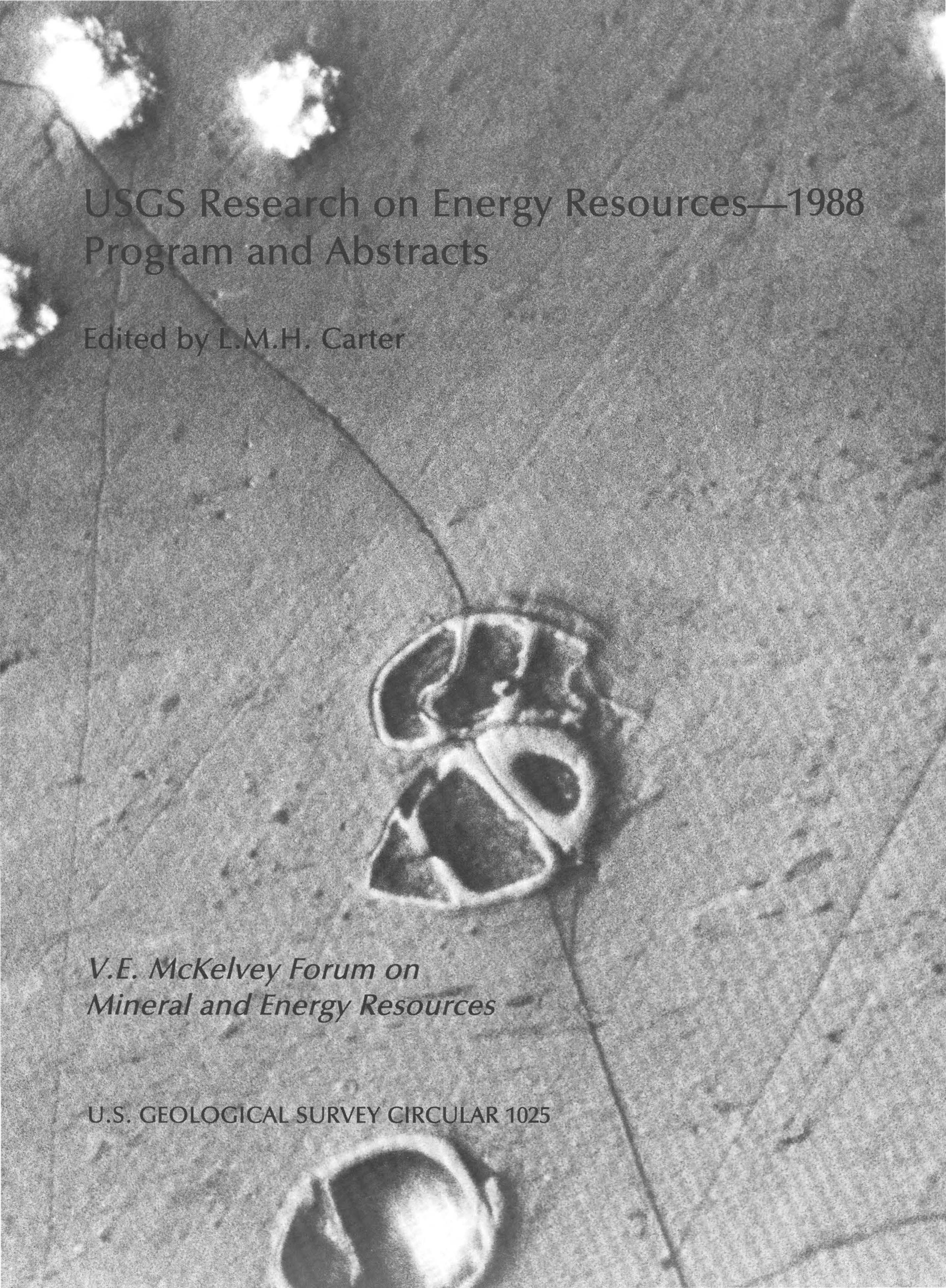
Dallas L. Peck
Director, Geological Survey

Sincerely yours,

William D. Bettenberg
Director, Minerals Management Service

USGS Research on Energy Resources—1988 Program and Abstracts

Edited by L.M.H. Carter



V.E. McKelvey Forum on Mineral and Energy Resources

U.S. GEOLOGICAL SURVEY CIRCULAR 1025

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
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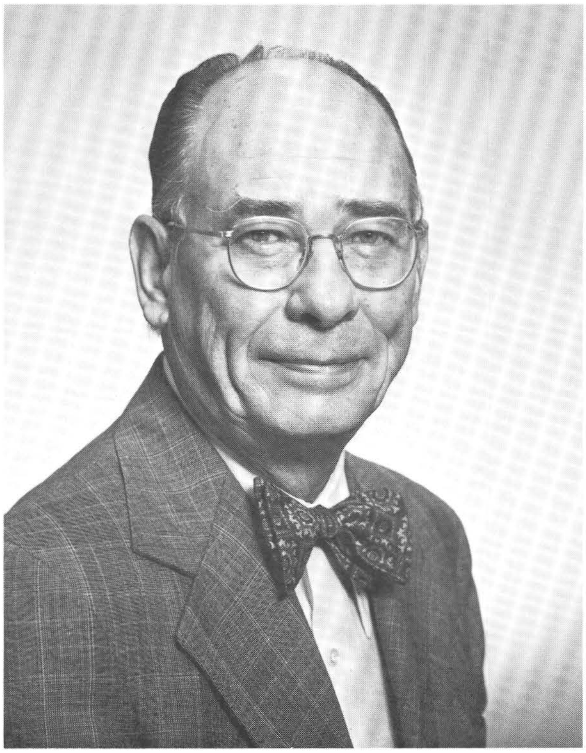
1988



A society's wealth depends on the use it makes of raw materials, energy, and especially ingenuity.
—V.E. McKelvey

FOREWORD

Dallas L. Peck, Director, U.S. Geological Survey

This volume contains summaries of lectures and posters included in the fourth V.E. McKelvey Forum on Mineral and Energy Resources, entitled "Roles of Geological Research in the Assessment of Energy Resources—1988." The McKelvey Forum serves as an opportunity for communication between the USGS and other earth scientists and users of the information, by presenting the results and progress of current USGS research as formal lectures. The informal poster sessions and more casual meetings provide an opportunity for concerned persons to meet individually with our scientists. I hope that the 1988 McKelvey Forum will help make our programs even more responsive to the needs of this community, particularly the fossil-energy industry, and that the interaction and cooperation begun here will continue and increase.

The Forum is named for former Director Vincent E. McKelvey in recognition of his lifelong dedication to the study of mineral and energy resources as research scientist, Chief Geologist, and Director of the U.S. Geological Survey. The Forum is an annual event which alternates between mineral and energy resources; this year the emphasis is on energy. Although the format and subject matter change somewhat from year to year, the primary purpose of the Forum remains the same: to encourage direct communication among USGS scientists, the representatives of other earth-science organizations, and interested individuals.

Energy programs of the USGS include investigations related to oil and gas, coal, geothermal sources, uranium-thorium, and oil shale. Our studies encompass the entire National domain, including the offshore Exclusive Economic Zone. The topics selected for this year's McKelvey Forum illustrate the breadth and depth of our research in energy resources. This year the program includes, among other subjects, (1) the results of the new joint MMS and USGS National assessment of undiscovered oil and gas in the United States; (2) new approaches to the application of organic geochemistry of petroleum source rocks, prediction of reservoir quality, and the entrapment of petroleum; (3) recent investigations of selected sedimentary basins including the Anadarko, Powder River, and Santa Maria basins; (4) new studies of coal depositional environment and new methodologies for evaluating available coal resources; (5) resource studies of offshore regions such as central California and the South Pacific island nations; (6) structural studies of the Midcontinent rift system and the early Mesozoic rift basins of the eastern seaboard.

I am excited about this continuing opportunity to illustrate and discuss our research with our colleagues in industry and academia; we welcome your suggestions for improving the McKelvey Forum.

V.E. McKELVEY FORUM—PROGRAM OF LECTURES AND DISCUSSIONS

DENVER, COLORADO, FEBRUARY 29, MARCH 1-2, 1988

Monday, February 29, 1988

4:00 p.m.	Registration, Radisson Hotel
5:00- 7:30 p.m.	Ice-breaker/Cash bar mixer

Tuesday, March 1, 1988

8:30 a.m.	Opening Session (Grand Ballroom, Radisson Hotel): Welcome and introductory remarks - *Gary W. Hill, Dallas L. Peck, Benjamin A. Morgan*
8:50	Keynote Lecture - *David A. White*
9:30	—Technical Session 1, Richard F. Mast, presiding
9:30	Estimates of undiscovered oil and gas resources for the onshore and State offshore areas of the United States *Richard F. Mast, G.L. Dolton, R.A. Crovelli, R.B. Powers, R.R. Charpentier, D.H. Root, and E.D. Attanasi*
10:00	Coffee Break
10:30	A rationale for the method of estimating the number of small undiscovered oil and gas fields *L.J. Drew, J.H. Schuenemeyer, and E.D. Attanasi*
11:00	U.S. energy supply from the perspective of world petroleum geology *Charles D. Masters*
11:30	The petroleum system—A classification scheme for research and resource assessment *Leslie B. Magoon*
12:00	Adjournment of technical session; luncheon
12:00	McKelvey Forum Luncheon, address by *Norman H. Foster*
1:45 p.m.	—Technical Session 2 (Grand Ballroom) Harold J. Gluskoter, presiding
1:45	Coastal Sumatra—A modern analog for the origin of Lower Pennsylvanian coal-bearing strata in the Eastern United States *C. Blaine Cecil, Sandra G. Neuzil, and others (all authors listed with printed abstracts by first authors Cecil and Neuzil)*
2:30	Effects of climate, tectonism, and variations in sea level on the formation of the Cretaceous coals of North America *Peter J. McCabe, Michael E. Brownfield, Dan E. Hansen, Robert D. Hettinger, Mark A. Kirschbaum, and J. David Sanchez*
3:00	Analcime in coal beds of the Wasatch Plateau, Utah—Geological and technological significance *Robert B. Finkelman*
3:30	Available coal resources—A pilot study *Jane R. Eggleston, M. Devereux Carter, and James C. Cobb*

PROGRAM OF LECTURES AND DISCUSSIONS (CONTINUED)

4:00	Identification and importance of coal bed gas, San Juan Basin, southwestern Colorado and northwestern New Mexico *Dudley D. Rice, Charles N. Threlkeld, and April K. Vuletich*
4:30	Abnormally high- and low-pressured oil and gas reservoirs—Examples from Rocky Mountain region *Charles W. Spencer*
5:00	Adjournment

Tuesday evening, March 1, 1988

7:30–10:30 p.m.	—Technical Session 3: 63 poster papers, with authors and kegs on tap

Wednesday, March 2, 1988

8:00 a.m	—Technical Session 4 (Grand Ballroom) D.L. Gautier, presiding
8:00	Inorganic and organic geochemical cycles in petroleum source rocks of the Cretaceous Western Interior seaway—Records of paleoceanographic change *Walter E. Dean, Michael A. Arthur, and Lisa M. Pratt*
8:30	Paleoenvironmental and source rock assessment of black shales of Pennsylvanian age, Powder River and northern Denver basins *J. L. Clayton, J.D. King, C.M. Lubeck, J.S. Leventhal, and T.A. Daws*
9:00	Potential petroleum source rocks in the Late Proterozoic Chuar Group, Grand Canyon, Arizona *Mitchell W. Reynolds, James G. Palacas, and Donald P. Elston*
9:30	Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska *Kenneth J. Bird, Leslie B. Magoon, and C.M. Molenaar*
10:00	Coffee Break
10:30	Dependence of sandstone porosity upon thermal maturity—An approach to prediction and interbasinal comparison of porosity *James W. Schmoker and Donald L. Gautier*
11:00	Diagenetic evolution of deep hydrocarbon-bearing rocks in the Ordovician Simpson Group, Anadarko basin, Oklahoma— Evidence from mineralogic, stable isotope, and fluid inclusion studies *Janet K. Pitman and Robert C. Burruss*
11:30	Low-temperature formation of illite—Implications for clay geothermometry and hydrocarbon generation *Christine E. Turner-Peterson, Neil S. Fishman, and Douglass E. Owen*
12:00	Adjournment of Technical Session 4
1:30 p.m.	—Technical Session 5 (Grand Ballroom) Robert B. Halley, presiding
1:30 p.m.	Offshore resource geology of selected South Pacific Island Nations—The USGS SOPAC program *H. Gary Greene, Michael S. Marlow, David W. Scholl, and John G. Vedder*

PROGRAM OF LECTURES AND DISCUSSIONS (CONTINUED)

2:00	Offshore resource geology of central California *David S. McCulloch and Stephen D. Lewis*
2:30	Crustal structure and deep rift basins of the midcontinent rift system—Results from GLIMPCE deep seismic-reflection profiles *J.C. Behrendt, A.G. Green, W.F. Cannon, D.R. Hutchinson, M.W. Lee, B. Milkereit, W.F. Agena, and C. Spencer*
3:00	Distribution and structure of early Mesozoic rift basins on the continental margin of the Eastern United States *K.D. Klitgord and D.R. Hutchinson*
3:30	Laramide thrusting of the Bighorn Mountains onto the Powder River Basin near Buffalo, Wyoming *J.A. Grow, E.N. Hinrichs, J.J. Miller, M.W. Lee, and S.L. Robbins*
4:00	Seismic stratigraphy of the Békés basin, Southeastern Hungary *Robert E. Mattick, János Rumpler, Antal Ujfalusy, Béla Szanyi, and Irén Nagy*
4:30	Conclusion of Forum

V.E. McKELVEY FORUM—POSTER SESSIONS

Atlantic and Pacific Marine Geology

Interpretation of seafloor processes in the Gulf of Mexico using the GLORIA sidescan sonar system
Bonnie A. McGregor and David C. Twichell

Banks, reefs, deltas, and fans—Jurassic-Cretaceous transition in the Baltimore Canyon trough
C. Wylie Poag, John S. Schlee, B. Ann Swift, Mahlon M. Ball, and Linda Sheetz

GLORIA survey off the East Coast of the United States
J.M. Robb, D.W. O'Leary, W.P. Dillon, P. Popenoe, E.A. Winget, J.S. Schlee, D.C. Twichell, P.C. Valentine, and K.M. Scanlon

Offshore resource geology of the Western United States—A new continental margins volume
David W. Scholl, Arthur Grantz, and John G. Vedder

Submarine canyons of the Florida Escarpment, eastern Gulf of Mexico
D.C. Twichell and L.M. Parson

GLORIA sonographic mosaics of the Bering Sea and the western Aleutian Arc and adjacent North Pacific
EEZ-Scan Bering Sea and Aleutian Arc Groups

Coal Geology—Coal Geochemistry

Petrographic and chemical character of Tertiary coals in northern California
Neely H. Bostick

Characterization of coals in the lower part of the Williams Fork Formation, Twentymile Park District, eastern Yampa coal field, Routt County, Colorado
Michael E. Brownfield and Ronald H. Affolter

Correlation of facies using chemical and maceral data in the C coal bed, Emery Coal Field, Utah
Sharon S. Crowley and Ronald W. Stanton

Basin evolution and upper Paleozoic coal deposits in the central Appalachian basin
Kenneth J. Englund and Roger E. Thomas

Organic geochemical studies of the early coalification of peat and associated xylem tissue
Patrick G. Hatcher, Harry E. Lerch, III, T.V. Verheyen, and M.A. Wilson

Supergene enrichment of sulfur in coal deposits of the Powder River Basin
Charles W. Holmes and Anthony B.Gibbons

Implications of trace-element concentrations in modern tree fern tissues for the origin of elements in vitrinites of the Pittsburgh coal bed
Paul C. Lyons and Curtis A. Palmer

The distribution of rare-earth elements in the Pittsburgh coal bed
James S. Mee, Curtis A. Palmer, and Charles L. Oman

POSTER SESSIONS (CONTINUED)

The Campbell Creek/No. 2 Gas/Peerless/Powellton coal bed correlation from the middle part of the Kanawha Formation of the central Appalachian basin
J.T. O'Connor

Selenium in coal from the Powder River Basin, Wyoming and Montana
C.L. Oman, R.B. Finkelman, S.L. Coleman, and L.J. Bragg

The association of uranium with organic matter in a uranium-rich peat bog in the Carson Range near Lake Tahoe, Nevada
W.H. Orem, R.A. Zielinski, and J.K. Otton

Trace-element analysis of vitrinite concentrates—New approach for determining organic and inorganic affinity
Curtis A. Palmer, Paul C. Lyons, and Janet D. Fletcher

Comparative quality of the Upper and Lower Freeport coal beds in the Appalachian basin
Brenda S. Pierce and Ronald W. Stanton

Preliminary facies analysis of the sequence of rocks below the upper Wyodak coal bed, Paleocene Fort Union Formation, southeastern Powder River Basin, Wyoming
Frances Wahl Pierce and Edward A. Johnson

Manganese binding by iron bacteria in wetlands—A potential analog for manganese-rich coal
E.I. Robbins, E.W. de Vrind, Hans de Vrind, and W.C. Ghiorse

Coal quality and distribution in Upper Cretaceous and Tertiary rocks, east-central North Slope, Alaska
Stephen B. Roberts

Pakistan—A coal geologists' paradigm
S.P. Schweinfurth, M.J. Bergin, W.O. Fredericksen, R.T. Hildebrand, E.R. Landis, W.F. Outerbridge, J.F. SanFilipo, F.O. Simon, P. D. Warwick, and C. Wnuk

Eocene lava and epigene mineralization alter Alaska's thickest known coal deposit
Gary D. Stricker and Ronald H. Affolter

Stratigraphy and facies analysis of Tertiary units, western Medicine Lodge Basin, Montana
Jean N. Weaver

Indigenous sources of fossil fuels, Sahel region of North Africa
Jean N. Weaver, Marion J. Bergin, Michael E. Brownfield, and Edwin R. Landis

Paleobotanical composition of some Pennsylvanian coal beds from the central Appalachian basin as an indication of paleoclimate
Richard B. Winston and Ronald W. Stanton

Petroleum Geology—Petroleum Geochemistry

Tertiary igneous intrusions and renewed petroleum generation in the western Delaware Basin, Texas
Charles E. Barker and Mark J. Pawlewicz

Hydrocarbon distribution in the Cretaceous-Tertiary Sagavanirktok Formation, North Slope, Alaska
T.S. Collett and K. J. Bird

POSTER SESSIONS (CONTINUED)

Burial history reconstruction of the Lower Cretaceous J sandstone in the Wattenberg Field, Colorado, "hot spot"
D.K. Higley and D.L. Gautier

Santa Maria Project, central California coast
C.M. Isaacs and R.G. Stanley

Kinetic models of organic reactions applied to burial history of sedimentary basins
J. David King

Organic geochemical studies of the Eastern U.S. early Mesozoic Newark Basin— Phase Two
R.K. Kotra

The role of thermal history in the preservation of oil at the south end of the Moxa arch, Utah and Wyoming—Implications for the oil potential in the southern Green River basin
B.E. Law and J.L. Clayton

Petroleum geology of the People's Republic of China
K.Y. Lee and C.D. Masters

Stratigraphic framework of the Pannonian sequence (Neogene), Békés basin, southeast Hungary
C.M. Molenaar, I. Révész, I. Bérczi, A. Kovács, Gy. K. Juhasz, I. Gajdos, and B. Szanyi

Estimation of paleogeothermal gradients and their relationship to the timing of petroleum generation, Eagle basin, northwestern Colorado
Vito F. Nuccio, Christopher J. Schenk, and Samuel Y. Johnson

Reconnaissance of Colorado Front Range bogs for uranium and other elements
Douglass E. Owen, R. Randall Schumann, and James K. Otton

Applying aromatic steroids to determination of thermal maturity of biodegraded heavy oils, tar sands, and bitumens
James G. Palacas, Donald E. Anders, and J. David King

Thermal maturation of the eastern Anadarko basin, Oklahoma
Mark J. Pawlewicz

Relation of major sea-level fall and regional unconformity to hydrocarbon accumulations, Upper Cretaceous Turner Sandy Member of Carlile Shale, Black Hills uplift
Dudley D. Rice and C. William Keighin

Sequential, time-slice paleogeography of northwest Borneo, Southeast Asia, as a basis for the delineation of oil and gas plays
Keith Robinson

A major Eocene suture in the southern Washington Cascades—Are hydrocarbon source rocks buried beneath volcanic flows?
Dal Stanley, Bill Heran, and Carol Finn

Tectonic history and petroleum potential of eastern Washington and Oregon
Marilyn E. Tennyson and Judith Totman Parrish

POSTER SESSIONS (CONTINUED)

Geology and petroleum resources of the Barents-northern Kara Shelf, U.S.S.R. and Norway
Gregory Ulmishek

Petroleum Resource Assessment—Resource Potential

Small field oil and gas resource estimation for the National Assessment
E.D. Attanasi and D.H. Root

Oil and gas potential of the continental margin, offshore Virginia
K.C. Bayer and R.C. Milici

Scientific studies relevant to the question of Antarctica's petroleum resource potential
John C. Behrendt

The use of basin classification and analog basins in petroleum resource assessment
Mark W. Bultman

An assessment of gas resources in low-permeability sandstones of the Upper Cretaceous Mesaverde Group, Piceance basin, Colorado
Ronald C. Johnson, Robert A. Crovelli, Charles W. Spencer, and Richard F. Mast

Assessment of gas contained in overpressured low-permeability reservoirs in the Greater Green River basin of Wyoming, Colorado, and Utah
B.E. Law, C.W. Spencer, R.A. Crovelli, R.F. Mast, G.L. Dolton, R.R. Charpentier, and C.J. Wandrey

Sedimentology—Clay Mineralogy

Phosphorus burial in the deep sea during the past 125 million years
James R. Herring, Walter E. Dean, and Michael A. Arthur

Sedimentology of and petroleum occurrence in the Lower Permian Schoolhouse Tongue of the Weber Sandstone, northwest Colorado
Samuel Y. Johnson, Christopher J. Schenk, Donald E. Anders, and Michele L. Tuttle

Basin analysis studies of Cambrian through Mississippian rocks, Powder River Basin, Wyoming and Montana
David L. Macke

Diagenetic transformations and phosphate mineral precipitation in marine lakes of the Palau Islands
W.H. Orem, W.C. Burnett, W.B. Lyons, W. Landing, and P. Chin

Relationship of clay-mineral diagenesis to temperature, age, and hydrocarbon generation—An example from the Anadarko basin, Oklahoma
Richard M. Pollastro and James W. Schmoker

Sedimentology of the Permian upper part of the Minnelusa Formation near Beulah, Wyoming—Analog for subsurface facies in the Powder River Basin
C.J. Schenk, J.W. Schmoker, J.E. Fox, and M.W. Lee

Diagenesis of sandstones in the Permian upper part of the Minnelusa Formation, West Mellott field, Powder River Basin, Wyoming
C.J. Schenk, R.M. Pollastro, and J.W. Schmoker

POSTER SESSIONS (CONTINUED)

Structural Geology—Geophysics

Abbreviations and conversion factors

bbo	billions of barrels of oil
mcf	thousand cubic feet
n.m.	nautical miles
tcf	trillion cubic feet
BOE	barrels of oil equivalent
COCORP	Consortium for Continental Reflection Profiling
DSDP	Deep Sea Drilling Project
EEZ	Exclusive Economic Zone
GLORIA	Geologic LOng Range Inclined Asdic
INAA	Instrumental neutron activation analysis
Moho	Mohorovičić discontinuity
NACS	North American Composite Shales
NCRDS	National Coal Resource Data System
TTI	Time Temperature Index (Lopatin

To convert	To	Multiply
miles	kilometers	1.6×miles
kilometers	miles	0.62×kilometers
feet	meters	0.3048×feet
meters	feet	3.25×meters
°C	°F	9/5 C+32
°F	°C	5/9 (F–32)

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Edited by L. M. H. Carter

Small Field Oil and Gas Resource Estimation for the National Assessment

E.D. Attanasi and D.H. Root

The latest U.S. National onshore oil and gas assessment prepared by the U.S. Geological Survey evaluates oil and gas at the play level for nearly all United States petroleum provinces. However, play analysis methods were restricted to fields of at least 1 million barrels of oil or 6 billion cubic feet of gas, for which there exists a relatively complete and accurate data set. Nonetheless, it was recognized that there were resources in fields smaller than these cut-offs, and estimates were made of resources within five small field-size classes: 31,500 to 62,500 barrels, 62,500 to 125,000 barrels, 125,000 to 250,000 barrels, 250,000 to 500,000 barrels, and 500,000 to 1,000,000 barrels of oil, or the barrels of oil equivalent in cubic feet of gas.

Although small fields are numerous, their data set is so incomplete and inaccurate that it was not practical to analyze their potential on a play basis. Instead, estimates were made for provinces.

The main assumption was that for each province there is a ratio, R greater than 1, such that the ultimate number of fields occurring in each class was R times as many as in the next larger class.

Estimates for the numbers of ultimately occurring fields in the classes larger than 1 million barrels of oil or 6 billion cubic feet of gas were derived from the data for past discoveries and the play estimates of remaining resources. From these estimates of the ultimate numbers of large fields, an estimate for R was calculated for each province. The ratio was then used to determine the ultimate number of fields in the small classes. Data available for the number of discovered fields was subtracted from the ultimate numbers to give the number of small undiscovered fields.

In order to enhance the economic utility of these projections, the number representing the expected value of undiscovered small fields in each province was allocated to four depth intervals, each of 5,000 feet. For each province, this allocation to depth intervals was in the same proportion as that of the discovered and estimated 1,000,000 to 5,000,000 barrel-of-oil-equivalent oil and gas fields.

The amounts of oil and gas in the small undiscovered fields were calculated by multiplying the midpoint volume of each of the five classes of fields by the number of fields in the class.

Tertiary Igneous Intrusions and Renewed Petroleum Generation in the Western Delaware Basin, Texas

Charles E. Barker and Mark J. Pawlewicz

Above-average paleogeothermal gradients in the western Delaware Basin, which are associated with numerous igneous intrusions and increased heat flow, have thermally matured rocks as young as Late Permian. Mean random vitrinite reflectance (R_m)-depth profiles of samples collected from boreholes throughout the Delaware Basin form two distinct groups. One group, with a 0.5 $\%R_m$/km gradient, is from the eastern portion of the basin, and the other, with a 0.7 $\%R_m$/km gradient, is from the western portion. The difference between the two groups is attributed to Tertiary thermal events that increased heat flow and reheated the rocks of the western Delaware Basin after uplift and erosion. Reheating of the Magnolia Cowden-1 borehole has caused R_m to vary from 0.6 % at 60 m (200 ft) near the top of the Guadalupian (Late Permian) to 2.8 % in Devonian rocks at 2,900 m (9,500 ft).

Post-Mississippian tilting has produced a thicker, mostly uneroded sedimentary section in the eastern portion of the Delaware Basin. In the western part of the basin, this tilting caused uplift and erosion that exposed the Upper Permian section, prior to Cretaceous time. Ages of igneous intrusions in the western half of the Delaware Basin show that they were emplaced 40–30 Ma, followed by Miocene to Holocene (23–0 Ma) basin-and-range type block faulting and associated high heat flow. Iso-reflectance contours cut across formation contacts in the western Delaware Basin, indicating that this heating is post-tectonic—that is, it occurred after eastward tilting and erosion had reduced burial depth. The R_m data and burial history reconstruction indicate that oil was generated during near-maximum burial in Permian time, and that the area was reheated by increased heat flow in Tertiary time. Maximum temperatures computed from R_m-depth relationships suggest that paleogeothermal gradients exceeded 40 °C/km (2.2 °F/100 ft) in Tertiary time. This reheating thermally matured rocks as young as Guadalupian in the western Delaware Basin and caused a second episode of petroleum generation. By this time, however, the Permian reservoir rocks and Ochoan evaporite seals had been partially to completely eroded. Consequently, it appears that this further maturation of the Permian source rocks occurred when conditions for trapping the generated petroleum were poor.

These data suggest that there is little potential for major petroleum discoveries in the western Delaware Basin. Further, this study reiterates that the petroleum potential of large areas can be assessed by simple geologic methods—thermal history reconstruction, and measurement of maturity of the sedimentary organic matter.

Oil and Gas Potential of the Continental Margin, Offshore Virginia

K.C. Bayer and R.C. Milici[1]

The prime objective of this study was to evaluate the oil and gas potential of the Virginia outer continental margin using publicly available seismic common depth point (CDP) lines. This reconnaissance seismic survey of eight cross-shelf profiles and two profiles subparallel to the coastline, totalling 729 statute miles (1,176 km), covered a Virginia offshore area of approximately 15,000 mi^2 (24,000 km^2).

Four stratigraphic horizons (near top of Upper Cretaceous, near top of Lower Cretaceous, near top of Jurassic, and an acoustic "basement" reflector) were correlated with horizons in the COST B–2 well; their depths were calculated from the travel times, and isopach and structural contours were compiled from the depth values. Preliminary results from the Shell 93–1 well, drilled through Cenozoic and Mesozoic strata offshore of Virginia, and from wells adjacent to the Virginia study area indicate low source-rock quality and thermal immaturity, suggesting deposition in oxidizing, open-shelf environments.

On the continental shelf, the acoustic basement reflector is generally the most dominant, continuous signal on the seismic profiles, suggesting a relatively dense, thick sequence of rock. If this sequence is a seal for hydrocarbons below, then several areas offshore of Virginia may be suitable drilling targets. Offshore Mesozoic basins, for example, the Norfolk Basin, may contain oil, gas, or both. Mesozoic basins offshore may contain sandstones and shales with scattered carbonate beds in sequences analogous to those in onshore basins. If depth of burial was insufficient to generate oil or gas in commercial quantities, these basins may still provide reservoirs for hydrocarbons migrating from other areas. In some areas structural traps may be present in older rocks; in addition, numerous stratigraphic targets occur in the Virginia offshore area where lower Mesozoic rocks wedge out against impervious rock masses.

If Middle to Upper Jurassic strata are potentially favorable for hydrocarbon generation, then the updip pinch-out of these rocks, approximately 18 mi (30 km) east of and parallel to the Virginia coast, may be a suitable target area.

A variety of structural anomalies in Mesozoic and Cenozoic strata below the continental slope appear to be the most attractive targets for exploration at present. Deep structural anomalies, such as the paleo-shelf edge, involving rocks at or below the acoustic basement, are potential hydrocarbon traps.

Evaluation and exploration of these structures will, however, require deep drilling to resolve the source bed and reservoir characteristics and possible migration pathways in their contained strata. The probability that the Virginia continental margin contains commercially recoverable quantities of oil and (or) gas is rated as fair (moderate) to poor (low).

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Scientific Studies Relevant to the Question of Antarctica's Petroleum Resource Potential

John C. Behrendt

No petroleum resources are known in Antarctica, and information is lacking to make reliable estimates of undiscovered resources. The Antarctic Treaty Consultative Parties are nearing completion on an Antarctic Minerals Regime; however, no economic exploitation is likely for several decades in the hostile Antarctic environment, even if prices return to the high levels of a few years ago. Only giant (about 70 million tons or 0.5 billion barrels) or more probably supergiant (about 700 million tons or 5 billion barrels) fields would be reasonable to consider as economic.

The tectonic history of Antarctica subsequent to the Gondwanaland breakup suggests that West Antarctica is the most likely area to contain petroleum resources, although East Antarctica cannot be excluded. Probably only the continental margins will be exploitable with present or soon-to-be-developed technology because of the several-kilometer-thick moving grounded ice sheet covering the rest of Antarctica. Since 1976, a number of countries have accelerated geophysical research programs over the continental margin, which are providing significant resource assessment information. These data and sparse drilling and bottom geologic samples suggest the presence of several kilometers of unmetamorphosed sedimentary rock (possibly of Cretaceous and Cenozoic age) beneath the Ross, Weddell, and Bellingshausen margins of West Antarctica, and beneath the Amery Ice Shelf—Prydz Bay area and rift basins beneath the narrow continental margin in East Antarctica. Aeromagnetic data indicate significant thicknesses of nonmagnetic sedimentary rock in several basins beneath the grounded ice sheet in East and West Antarctica. Diatoms and other microfossils present in moraines in the Transantarctic Mountains suggest the presence of Late Neogene sediments in the basins beneath the East Antarctic ice sheet, despite the onset of continental glaciation in the Oligocene.

Several Deep Sea Drilling Project (DSDP) holes into the Ross continental shelf have shown the presence of Tertiary marine and nonmarine sedimentary rocks as old as Oligocene overlying early Paleozoic basement. Shows of gas in the DSDP holes cannot be considered evidence of any hydrocarbon resources, but analyses of thermogenic hydrocarbons were reported from samples taken offshore of the northern Antarctic Peninsula. As present and future geophysical and geologic studies outline possible prospective areas, scientific studies are needed of hazards associated with geologic, meteorological, and oceanographic conditions, as well as ecosystems that might be adversely affected were petroleum development to occur. Examples of geologic hazards identified in several offshore areas include active faults in the Ross Sea continental shelf, gas hydrate beneath the continental slope off Wilkes Land, and iceberg scour marks on the sea bottom observed in two areas at depths greater than 500 m.

Crustal Structure and Deep Rift Basins of the Midcontinent Rift System—Results from GLIMPCE Deep Seismic-Reflection Profiles

J.C. Behrendt, A.G. Green,[1] W.F. Cannon, D.R. Hutchinson, M.W. Lee, B. Milkereit,[1] W.F. Agena, and C. Spencer[1]

Interpretation of GLIMPCE seismic-reflection profiles crossing western, central, and eastern Lake Superior and the northern end of Lake Michigan indicates that the midcontinent rift system (MRS) of volcanic and interbedded post-volcanic sedimentary rock of Keweenawan age is extensive. The rift deposits beneath Lake Superior are thicker and extend to greater depths (at least 32 km) than elsewhere along the MRS and perhaps anywhere else in the world. The thick volcanic units that make up the bulk of the rift deposits are areally extensive and continuous for lengths as great as 70 km on individual profiles. Lower crustal reflections vary in strength, distribution, and continuity along the rift axis, perhaps indicating variable amounts of crustal extension and mafic underplating accompanying rift formation, as suggested by many modern rift environments.

Times to Moho vary along strike from 11.5 to 14 seconds (about 37–46 km) in the west to 17 s in the center (about 55 km) and 13 to 15 s (about 42–49 km) in the eastern end of Lake Superior. Moho is least well defined in the reflection data beneath northern Lake Superior, at the pronounced bend in the MRS, where crustal thickness is greatest and the lower crustal reflections are the most complex. The prerift crust is 25–30 km thinner beneath the central rift than beneath its flanks, providing evidence for crustal extension by factors of about 3 to 4.

Total crustal thickness, 37–56 km, is considerably greater than the thicknesses reported for Phanerozoic continental rifts, and differs also in being equal to or greater than that of the surrounding (presumably unextended) regions. The MRS deposits may have analogs

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with thick wedges of volcanic and clastic rift deposits buried beneath modern passive continental margins and with volcanic wedges of seaward-dipping reflectors found at continent/ocean junctions.

Petroleum Geology of the Northern Part of the Arctic National Wildlife Refuge, Northeastern Alaska

Kenneth J. Bird, Leslie B. Magoon, and C.M. Molenaar

The northern part of the Arctic National Wildlife Refuge and adjacent Native lands, an area between the Brooks Range and the Beaufort Sea encompassing about 2.4 million acres, is judged to have the geologic characteristics of a major petroleum province. Except for the undeformed northwest quarter, the area is involved in an east-west- and northeast-trending, north-verging imbricate fold and thrust-fault system related to Brooks Range deformation.

The most likely petroleum-reservoir rocks are sandstones of Cretaceous and Tertiary age and intra-basement carbonate rocks of pre-Mississippian age. Clastic and carbonate reservoir rocks of Mississippian to Triassic age, similar to the reservoir rocks at Prudhoe Bay, are truncated by Early Cretaceous erosion related to rifting; these rocks are expected to occur in the southern part of the area considered.

Analyses of hydrocarbons from oil seeps and oil-stained rocks in outcrop suggest that three types of oil are present, all dissimilar to oils from the Prudhoe Bay area. The most important source rock for oil is postulated to be the Tertiary(?) and Cretaceous Hue Shale. With a present-day geothermal gradient of about 30 °C/km (1.6 °F/100 ft), oil generation is expected to occur between depths of 3.7 and 6.9 km (12,000–22,500 ft), mostly within the thick Cretaceous and Tertiary (Brookian) sequence. Oil generation, accompanied by clay-mineral transformation and abnormal-fluid-pressure development, probably began about 50 Ma at the southern edge of the coastal plain and progressed northward, reaching the coastline about 10 Ma.

Seismic data indicate that many more structures are present than have been previously suspected. Short-wavelength folds, perhaps numbering in the hundreds, are complexly faulted and involve mostly Brookian rocks. These folds overlie one or more regionally extensive low-angle faults that structurally detach them from a relatively small number of long-wavelength, moderately faulted structures composed mostly of pre-Brookian rocks. Structural traps are believed to have formed before, during, and after oil generation and migration.

Mean value estimates of in-place oil and gas resources for a 1.5-million acre part of this area are 13.8 billion bbl of oil (bbo) and 31.3 trillion ft^3 of gas. The amount of economically recoverable oil in 26 seismically mapped structures in estimated at 3.2 bbo (mean value). Evaluation showed that natural-gas resources are not economically recoverable.

Petrographic and Chemical Character of Tertiary Coals in Northern California

Neely H. Bostick

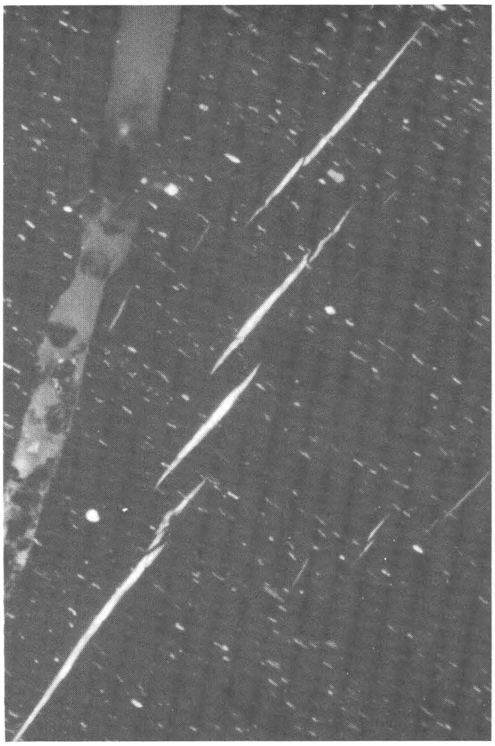
The only two significant coalfields in northern California are accessible today though their period of most active mining was from 1870 to 1900. Parts of the Mount Diablo field, 30 miles east of San Francisco, are open in a public park administered by mining engineers, and part of the Ione field 60 miles farther east is exposed because the lignite has been worked anew since 1947 for montan wax. Minor coal occurrences outside these fields are accessible in outcrop.

The Mount Diablo subbituminous and the Ione lignitic coals lie within Eocene sequences mainly composed of sandstone. The Ione lignites are widely known for their unusual wax production. Petrographically, however, the Mount Diablo and Ione coals are similar. They contain very high amounts of liptinite (originating from spores, cuticle, resin, and wax), but few layers of clean huminite (wood, bark, root material). In both, the total amount of liptinite is difficult to analyze because much of it is fine broken detritus. The Ione lignites contain thin as well as massive cutinite bands, blebs of probable cuticular wax, dispersed microspores, isolated oval resin bodies, and peculiar "horsehair" layers of vesiculated resin rodlets. The dominant identifiable liptinites in the Mount Diablo coals are microspores and resins, and they show an unusual display of exsudatinite (from resinite) that filled fractures in two directions normal to bedding. Both coals have distinct microscopic structure parallel to the gross bedding but do not contain prominent beds of massive "wood" and fine attritus that are characteristic of many other United States coals. Especially in the Ione samples, the structure suggests accumulation of a full gamut of plant organs and tissues but severe decay of most humic tissues. The Mount Diablo coal contains abundant pyrite that occurs as dispersed framboids, veins that filled bedding partings during early diagenesis, and later cleat fillings. The Ione lignite has little pyrite.

Another northern California coal formerly mined near Covelo, 140 miles north of San Francisco, is within a fault-bounded sliver of probable Eocene and Miocene strata within the coastal Franciscan terrain. The coal is much less liptinitic than the Ione or Mount Diablo coals, and it has very abundant fungal sclerotia. It contains an unusual petrified log within the coal. Lignites still farther north, near Hayfork and Douglas City in Trinity County, are entirely woody where sampled; they occur in shallow basins and may be Pliocene.

Hydrogen indexes of 100–200 and oxygen indexes of 50–250, from programmed pyrolysis, confirm the humic composition of the Hayfork, Douglas City, and Covelo coals. In contrast, the Mount Diablo and Ione coals contain hydrogen indexes of 200–400, and isolated "chocolate" layers at Ione have unusually high hydrogen indexes of 600 like pure resinite. The wax product from Ione has twice the hydrogen of resin layers. After crushing and wax extraction, the lignite residue retains a hydrogen index of 200, and many liptinite fragments are not visibly altered by extraction; the wax product apparently is derived mainly from actual cuticular waxes, not from the hydrogen-rich resins or microspores.

These northern California coals display great compositional diversity: some have very high content of liptinite, including wax; others consist of intact tree trunks and roots; some layers are mainly pollen and spores or resin. The few analyses reported for other California coals indicate that some of them also may have a high content of liptinite. Thus the main interest for mining is in the hydrogen-rich California coals, which yield chemical specialty products. The total coal resource in California is small, but the coal-based wax industry at Ione is important nationally; and it may lead the way to uses more valuable than combustion for other special coals in the United States. A second interest is that these coals would have served as petroleum source rocks where they were deeply buried. The source-rock potential of a given volume of these coals may be as high



This Eocene coal from Mount Diablo, California, has a relatively high content of primary plant resins like many Tertiary coals. This resinite fluoresces bright orange-yellow (white in these photos) when illuminated under the microscope by ultraviolet or blue light. Compaction during peat-lignite-coal diagenesis causes injection of the resinite into tension fractures adjacent to resin bodies, as in left photo, as well as movement of resin or resin products into "tectonic" fracture systems such as the in-echelon fractures on the right. The bulk of this coal is fiine layers of highly biodegraded plant debris; the layering shows well in these photos because of the fine white flecks, mostly plant microspores, that fluoresce almost as brightly as the resinite. Polished section, water immersion optics, mercury vapor illuminator; left photo 0.12×0.18 mm, right 1.4×2.1 mm. [Diagonal gray band is plastic used to mount the coal for examination.] By Neely H. Bostick.

as 15 times that of shales with a comparable type of organic matter favorable for generating oil.

Characterization of Coals in the Lower Part of the Williams Fork Formation, Twentymile Park District, Eastern Yampa Coal Field, Routt County, Colorado

Michael E. Brownfield and Ronald H. Affolter

Fifty-five bench channel and core samples were collected and analyzed from three mine localities in the Twentymile Park district, eastern Yampa coal field, northwest Colorado. These alluvial plain coals of the Upper Cretaceous Williams Fork Formation consist of (from top to bottom) the Lennox, Wadge, and Wolf Creek beds. The Wadge and Wolf Creek beds are overlain by lagoonal and nonmarine sediments and have similar elemental composition. Both are low in sulfur (Wadge, 0.46; Wolf Creek, 0.65 percent) and ash (Wadge, 8.5; Wolf Creek, 10 percent) content. The upper portion of the Lennox coal is burrowed and is directly overlain and influenced by a bioturbated marine transgressive sandstone. The Lennox bed has a higher mean sulfur content (2.67 percent) and lower mean ash content (6.4 percent), and higher contents of Fe, Hg, As, and Br (9, 3.5, 3.8, and 2 times higher respectively) when compared to the Wadge bed and higher contents of Fe, Hg, and As (5.5, 3.5, and 2.3 times higher respectively) when compared to the Wolf Creek bed.

X-ray diffraction analysis of low-temperature ash (LTA) and parting material reveals a predominance of well-crystallized kaolinite and quartz, and minor amounts of highly expandable clay minerals for all three beds. Sanidine, plagioclase (andesine?), barite, gypsum, pyrite, and apatite were found in the coal LTA and parting material. The Lennox bed LTA contained pyrite and ankerite/dolomite when compared to the LTA from the Wadge and Wolf Creek beds.

Several altered volcanic-ash partings—tonsteins—were found in both the Wadge and Wolf Creek coals. Coal from the Wadge bed near the volcanic-ash partings shows barium and strontium contents 6 times higher and phosphorus contents 12 times higher than the average values for these elements from other Yampa field coals. X-ray diffraction, chemistry, and scanning electron microscope with energy-dispersive X-ray capability indicate the presence of hydrated aluminum-phosphate minerals of the crandallite group. The crandallite minerals occur as 1- to 3-micrometer anhedral to subhedral grains. Energy-dispersive X-ray data indicate that the crandallite group minerals present in the Wadge bed are mainly crandallite with minor amounts of gorceixite. That all samples displayed variable Ba, Ca, and Sr contents supports a solid solution mode of occurrence. The enrichment of Ba, Sr, and P is, in part, the result of the alteration of apatite-bearing air-fall tuffs that were deposited into the reducing environment of the coal swamp. The close association of the crandallite minerals with the clay fraction and the lack of evidence of these minerals replacing kaolinite suggest an authigenic origin. The crandallite minerals probably formed during early diagenesis of the peat swamps and were localized in and near kaolinitic altered volcanic-ash partings.

The Use of Basin Classification and Analog Basins in Petroleum Resource Assessment

Mark W. Bultman

Two things are important for assessing the amount of ultimately producible petroleum from an unexplored basin. First, the size distribution of oil fields in the basin will indicate the nature of hydrocarbon occurrence in the basin. Second, the richness factor for the basin (ultimately producible oil per unit volume of sediments) controls the amount of oil in the basin and is directly related to the oil field size distribution and the total number of oil fields in the basin.

In general, the oil field size distribution and richness factor of an unexplored basin can only be estimated by analogy, through the use of an analog basin. Considering the tectonic and geologic histories of the unexplored basin and possible analogs leads to a choice of a working analog.

In the analysis described here, the sample distribution of oil field sizes from basins in the contiguous United States was used to test the hypothesis that basins with similar tectonic settings have similar oil field size distributions and similar richness factors. The primary source of data used in the analysis was a 1981 excerpt from the TOTL file of the Petroleum Data System of North America.

A flexible three-parameter function, the first derivative of the Richards growth function, was used to model the distribution of oil field sizes within the sedimentary basins of the contiguous United States. The Richards function allows oil field size distributions which are right or left skewed as well as symmetric to be represented quite accurately. The Richards function was reparameterized in order to obtain parameters directly related to the geometric properties of the curve.

The most recent version of the Klemme basin classification system (published in 1983 by H.D.

Klemme) was used to place petroleum-producing basins of the United States into their appropriate tectonic settings. The parameters of the Richards function were used to compare basins both within and across these tectonic settings. These parameters were found to be related to the tectonic setting of the basin to some extent.

Classical multidimensional scaling was applied to the parameterizations of the oil field size distributions in the basins. This technique allowed distance between distributions to be represented in two dimensions and suggested a basin classification system based on the oil field size distributions of the basins. This classification system consists of the following five categories: (1) craton interior shallow and craton margin shallow (foreland) basins; (2) craton interior deep basins; (3) craton margin deep basins; (4) craton margin-Rocky Mountain basins; (5) convergent margin rifted basins. This is similar to Klemme's 1980-version classification system, except that Klemme's Gulf Coast "downwarp" basins could not be differentiated from craton margin deep basins.

The ultimately producible oil from each basin was estimated using production data from the Petroleum Data System, and this estimate, in turn, was used to create a richness factor for each basin. In general, richness was found to be extremely variable, both within and across tectonic basin types. Rifted convergent margin basins displayed a much higher richness factor than other basins, but still displayed a large amount of intra-group variance in the richness factor.

It is possible in some cases to use geologic analogy to transfer the sampled oil field size distribution from a mature analog basin to an unexplored, frontier basin. That the richness factor of a basin is not strongly correlated to the basin's tectonic setting, however, indicates that a basin may need to be at least partially explored before techniques using geologic analogy can be of any use in petroleum resource assessment. An *a priori* choice of richness factors based on tectonic setting alone may result in very misleading resource estimates.

The Midcontinent Rift in the Lake Superior Region—Structural Interpretation from Deep Seismic Reflection Profiling

W.F. Cannon, John Behrendt, and A.G. Green[1]

Deep seismic reflection profiling in Lake Superior and Lake Michigan was conducted in August and September 1986 as part of the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE). The surveys were funded by the U.S. Geological Survey and the Geological Survey of Canada.

Data were recorded for 20 seconds so that structures as deep as about 60 km could be detected. The profiles reveal clear images of the 1.1-b.y.-old Keweenawan rocks within the rift, and of fault and fold structures that produced rift basins that are locally as much as 30 km deep (fig. 1).

Sections of basalt, as thick as 20 km, produce very strong packages of layered reflectors that can be traced to or correlated with basalt sequences on land. Sedimentary

[1]Geological Survey of Canada, Ottawa, Ontario.

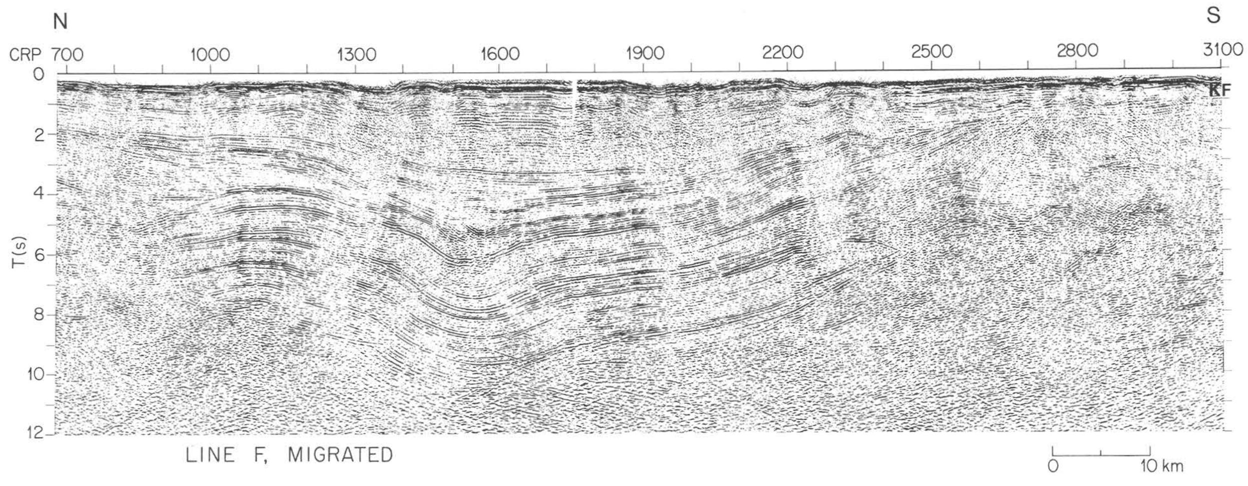


Figure 1. A portion of a reflection profile in eastern Lake Superior. Very strong reflectors are from a thick section of Keweenawan basalt and extend as deep as about 30 km beneath CRP 1600. Less reflective sedimentary rocks overlie the basalts and are as much as 8 km thick.

sequences as much as 10 km thick overlie the basalt and also occur in flanking basins. The profiles clearly show major graben-boundary growth faults which were active throughout most of the volcanic activity, so that the greatest thicknesses of basalt are within the central grabens of the rift and much thinner basalt sections occur flanking the grabens.

Subsidence of central rift grabens was highly variable along the rift. In western Lake Superior subsidence was highly asymmetrical: the north side of the graben subsided much more than the south side. The sense of asymmetry changes abruptly along strike from the western to the central part of the lake; there, subsidence was greatest on the south. Beneath eastern Lake Superior the structure is symmetrical, indicating uniform subsidence.

These relationships, along with the gravity expression of the rift, indicate that subsidence occurred as separate, independent blocks, each with its own subsidence history. The volcanic and sedimentary fill of the rift can be expected to change substantially along the rift trend in response to these varying subsidence histories and varying graben geometries.

Allogenic Processes in the Central Sumatra Basin—A Modern Analog for the Origin of Lower Pennsylvanian Coal-Bearing Strata in the Eastern United States

C. Blaine Cecil, Frank T. Dulong, James C. Cobb,[1] Supardi,[2] and Peter Turnbull[3]

The first phase of a study of modern analogs of coal formation was conducted in coastal Sumatra and the Straits of Malacca during the summer of 1987. This region was selected for study because the geologic setting appears to be analogous to that of a variety of coal-bearing sequences. The study area covers approximately 30,000 km^2 within the central Sumatra basin. The study area is bounded on the southwest by upland soils that are at the inland margin of coastal peat deposits, on the northwest by the Siak River, on the southeast by the Kampar River, and on the northeast by the Straits of Malacca. The bounding rivers are estuaries that are strongly influenced by tides (>2 m, 80 km inland from the coast).

Allogenic processes of subsidence, climate, and eustacy control both physical and chemical sedimentation in the region. Subsidence of the central Sumatra basin is associated with wrench faulting and oblique subduction along the Sunda Trench. The tropical everwet climate of the region is the result of the permanent equatorial low-pressure zone (tropical convergence). Eustatic changes in sea level appear to have occurred during the last 5,000 years.

On the basis of data from 36 marine and estuarine bottom cores, sediments deposited by physical processes have a texture range of clay to coarse sand and a mineralogy comprising clay minerals and quartz. Of the 36 cores, shell fragments were found in only the top of two cores from the Straits of Malacca. Chemical sediments consist of domed-peat on the coastal plain and on offshore islands (Neuzil and others, this volume).

Physical sedimentation is controlled by tidal currents in the rivers and by tidal and geostrophic currents in the Straits of Malacca. Eroding coastlines in the area are indicative of marine transgression. The bottoms of the Siak River, the Straits of Malacca, and the associated inter-island straits are also erosional, due to strong tidal currents. Sediment reworking and deposition are limited to the estuarine portion of the Kampar River, the estuary-mouth bar of the Siak River, and the confluence of the inter-island straits associated with the Straits of Malacca. All our observations indicate that the modern sedimentary system is sediment starved. The available sediment appears to be transported by tidal and geostrophic currents northwestward through the Straits of Malacca toward the Andaman Sea.

Many of the conditions in the study area appear to be analogous to those that controlled sedimentation for the Lower and lower Middle Pennsylvanian strata of the Eastern United States. These conditions include a tectonically active basin, a tropical everwet climate, and eustatic changes in sea level. The interaction of these allocyclic processes in Sumatra have resulted in a sediment-starved, tidally dominated sedimentary system in which thick, laterally continuous peat deposits form contemporaneously with extensive marine erosion. Such conditions may have been responsible for the formation of most of the Lower Pennsylvanian coal beds and for erosion that led to the Mississippian-Pennsylvanian unconformity in the east-central and southern Appalachian basin. Our data are also consistent with a tidal-origin interpretation for most of the quartzose sandstones of the Upper Mississippian and Lower Pennsylvanian of the central and southern Appalachian basin.

[1]Kentucky Geological Survey, Lexington, KY.
[2]Directorate of Mineral Resources, Bandung, Indonesia.
[3]P.T. Utah Indonesia, Jakarta, Indonesia.

Paleoenvironmental and Source Rock Assessment of Black Shales of Pennsylvanian Age, Powder River and Northern Denver Basins

J.L. Clayton, J.D. King, C.M. Lubeck, J.S. Leventhal, and T.A. Daws

Thin Middle Pennsylvanian (Desmoinesian) organic-rich black shales (cumulative thickness <50 ft) underlie much of the northern Denver basin and southeastern Powder River Basin. In the Powder River Basin, these shales are part of the middle member of the Minnelusa Formation. During Desmoinesian time, the present-day area of the southeastern Powder River Basin and Nebraska was a shallow, at times highly saline, restricted sea. In contrast, in the present-day area of northeastern Colorado, black shales were deposited in a marine environment with normal salinity which was probably continuous with the midcontinent Pennsylvanian sea.

Assessment of paleoenvironment has been carried out using organic geochemical parameters. Shales deposited in the restricted basin setting contain abundant porphyrins (25,000–30,000 ppm relative to total extractable organic matter) and significant quantities of aryl isoprenoids. The aryl isoprenoid compounds (1) are evidence for the presence of the sulfur bacteria families Chlorobiaceae and possibly Chromatiaceae and (2) indicate that euxinic conditions existed in the water column. High ratios of sulfur to carbon in the shales support this interpretation. In contrast, extracts from black shale in the normal sea to the south contain lower porphyrin concentrations (generally less than 1,000 ppm), and aryl isoprenoids are minor constituents or are absent. Sulfur/carbon ratios in these latter shales are similar to those observed for normal marine shales (that is, not euxinic conditions). Other paleoenvironmental indicators (sterane composition, alkane distribution) are consistent with these observations.

Bulk organic matter in the black shales from both environments is type II and has good source potential for generation of liquid hydrocarbons during catagenesis. Pyrolysis yields of 50 kg/ton (50,000 ppm) are common, and in some shales, yields reach 100 kg/ton (100,000 ppm).

Hydrocarbon Distribution in the Cretaceous-Tertiary Sagavanirktok Formation, North Slope, Alaska

T.S. Collett and K.J. Bird

New insights on the Sagavanirktok Formation as an important North Slope hydrocarbon reservoir rock unit are provided by C.M. Molenaar and others' 1986 subsurface correlation sections and ongoing USGS studies of gas hydrates and basin evolution. Detailed correlation sections in the Prudhoe-Kuparuk region and analyses of gas samples show that more heavy oil resides in Sagavanirktok sandstone reservoirs than previously reported, that several areally extensive gas hydrate deposits are present, and that the gas in the hydrate deposits likely originated through a combination of biogenic and thermogenic processes.

Throughout Cretaceous and Tertiary time on the North Slope, clastic debris shed northward from the rising ancestral Brooks Range filled the adjacent foredeep and prograded northeasterly across the subsiding Barrow arch to form a passive margin sequence, collectively known as the Brookian sequence. The nonmarine to shallow-marine Sagavanirktok Formation and its finer grained marine partial equivalent, the Canning Formation, form one of the thickest (0–2,700 m) clastic wedges in this sequence. The Sagavanirktok Formation consists of Late Cretaceous through Tertiary shallow-marine shelf and delta plain deposits composed of sandstone, shale, conglomerate, and coal. The areal distribution of the Sagavanirktok is limited to the coastal plain of the eastern half of the North Slope and the adjacent continental shelf.

Hydrocarbon occurrences within the Sagavanirktok Formation have been known since early exploratory drilling in the Prudhoe Bay area, and from earlier studies of outcrops to the south. Two oil-bearing sandstone intervals in wells from the Kuparuk area, informally named the West Sak and Ugnu sands, are estimated by ARCO Alaska to contain an in-place oil volume of 21 to 36 billion barrels. The oil in the West Sak sands ranges from 16 to 22 degrees API gravity and contains methane through pentane gases in solution. Oil in the lower Ugnu sands ranges from 8 to 12 degrees API gravity, and methane is the only gas in solution. Our analysis of well logs shows that the West Sak and Ugnu sands are not the only oil-bearing horizons within the Sagavanirktok of the Kuparuk River area: in some wells, rock units stratigraphically above the Ugnu sands contain oil columns more than 20 m thick. Outside the Kuparuk River area, the Sagavanirktok Formation is also oil bearing at Milne Point, Point Thomson, and east of the Kuparuk River oil field in the Prudhoe Bay oil field area.

Gas hydrates, crystalline compounds of water and gas, occur within the Sagavanirktok Formation. Direct evidence comes from a core recovered by Exxon Corporation in the Northwest Eileen-2 well, located 25 km west of Prudhoe Bay, and indirect evidence has been obtained from our analysis of open-hole geophysical logs—the most useful of these being the resistivity, acoustic transit-time, and the gas chromatograph on the mud log. We have mapped six laterally extensive gas hydrate accumulations in the Prudhoe-Kuparuk area. One rock unit in the southern part of the Kuparuk area contains gas hydrate, coal, and oil.

Previous investigators have suggested that the oil, and presumably the associated gas, within the Cretaceous and Tertiary sandstones of the Prudhoe-Kuparuk area were "spilled" from the underlying Prudhoe Bay Sadlerochit structure as a consequence of regional tilting during mid to late Tertiary time. Our analyses of canned drill-cutting samples provided by ARCO Alaska from several development wells in the Kuparuk River oil field suggest that the gas hydrates contain a mixture of biogenic and thermogenic gases. The gas in the Sadlerochit is thermogenic; therefore, not all of the gas in the Sagavanirktok Formation is from the underlying Prudhoe Bay Sadlerochit structure.

Correlation of Facies Using Chemical and Maceral Data in the C Coal Bed, Emery Coal Field, Utah

Sharon S. Crowley and Ronald W. Stanton

Facies in 11 cores of the C coal bed, Ferron Sandstone Member of the Mancos Shale (Cretaceous) were correlated using cluster analysis of chemical and maceral data. The use of chemical and maceral data enabled correlations to be made that were more precise than previous correlations based on the physical description of the cores. Chemical data for 26 elements[1] were determined in 146 coal and 40 rock samples. The data were reported on (or calculated to) a sample ash basis from atomic absorption, emission spectrographic, X-ray fluorescence, or neutron activation analyses. Maceral data included point counts of 23 macerals (using reflected white and fluorescent light on polished pellets) for 14 pairs of coal samples taken from above and below tonsteins. The results indicate that facies within the C coal bed can be delimited by their chemical and maceral compositions, and that these compositions were apparently affected by volcanic ash falls. A cross section of 5 of the 11 cores is depicted in figure 1.

Q-mode cluster analysis of the chemical data (grouping of samples into clusters of similar composition) produced seven major clusters with distinctive chemical characteristics (fig. 1). The following comparison of clusters is based on the mean values of elements in each cluster. Clusters I and II contain a large number of samples that have a high ash content; these clusters are characterized by relatively low levels of all 26 elements except for Al (Al_2O_3=35 percent in cluster II). Cluster III consists primarily of coal samples that contain intermediate levels of the elements studied, with the exception of relatively high Li values of 118 ppm. Cluster IV samples generally came from the lower part of the coal bed, and they were commonly taken from localities adjacent to tonsteins or shales associated with tonsteins. These samples are also characterized by intermediate levels of all 26 elements. Cluster V, comprising samples taken from near the base and top of the C coal bed, contains relatively high levels of several elements including Ni (105 ppm), Co (78 ppm), Zn (140 ppm), and Cr (83 ppm). Cluster VI consists of four samples, taken directly below the "upper" tonstein in all but one case. This cluster is characterized by high average concentrations of Zr (1,240 ppm), Nb (66 ppm), and Ce (485 ppm) compared to the other clusters. Cluster VII comprises six coal samples taken directly adjacent to tonsteins in all cases, primarily between the "doublet" tonsteins. This cluster contains relatively high concentrations of Zr (765 ppm), Nb (63 ppm), Th (81 ppm), and Hf (22 ppm). Leaching of volcanic ash or incorporation of ash in peat layers is interpreted to have contributed to high levels of several elements that characterize clusters VI and VII. For example, the tonstein minerals zircon and ilmenite may have provided sources for high levels of Zr and Nb, respectively, in cluster VI.

Q-mode cluster analysis of the maceral data produced two major clusters (fig. 1). Cluster A samples contain abundant inertinites (mean values=38 percent inertinites, 57 percent vitrinites, 5 percent exinites) and were taken directly below tonsteins, whereas cluster B samples contain abundant vitrinites (mean values=14 percent inertinites, 81 percent vitrinites, 5 percent exinites) and generally came from above tonsteins. The inertinites are composed primarily of semifusinite, a maceral generally accepted as forming under oxidizing conditions. Abundant semifusinite below tonsteins may reflect better drained swamp conditions than those that existed after the volcanic ash falls.

Inorganic and Organic Geochemical Cycles in Petroleum Source Rocks of the Cretaceous Western Interior Seaway—Records of Paleoceanographic Change

Walter E. Dean, Michael A. Arthur, and Lisa M. Pratt

Two major transgressive episodes in the Cretaceous western interior seaway resulted in the deposition of organic-carbon-rich pelagic carbonate

[1]Sm, Eu, Ce, V, U, Ni, Co, Yb, Lu, Y, Be, Sc, Nb, Zr, Hf, Th, Ta, Se, Pb, Zn, Cr, Li, Al, Cu, Ti, Ga.

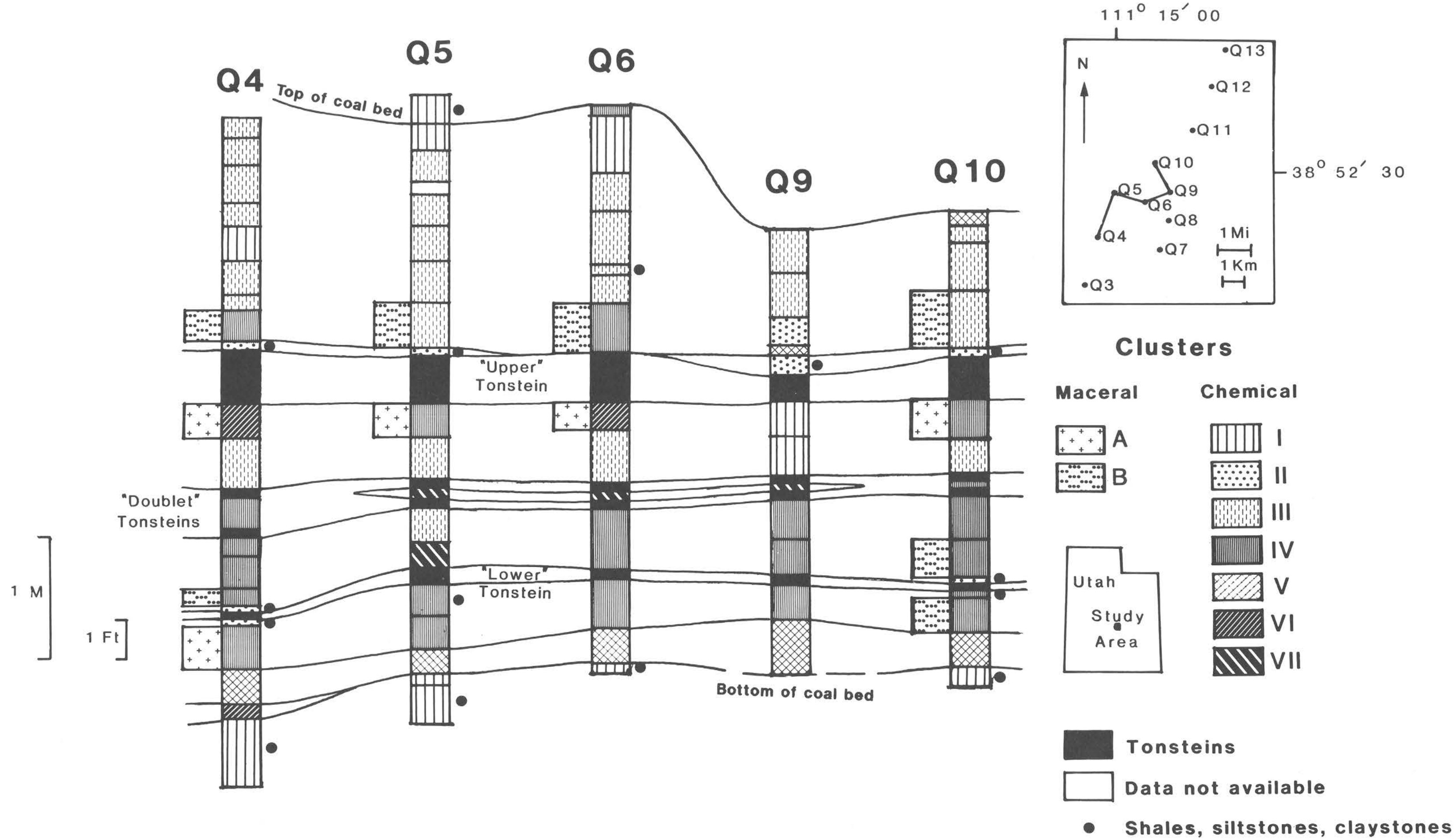


Figure 1. Correlation of samples from five cores of the C coal bed using chemical and maceral clusters.

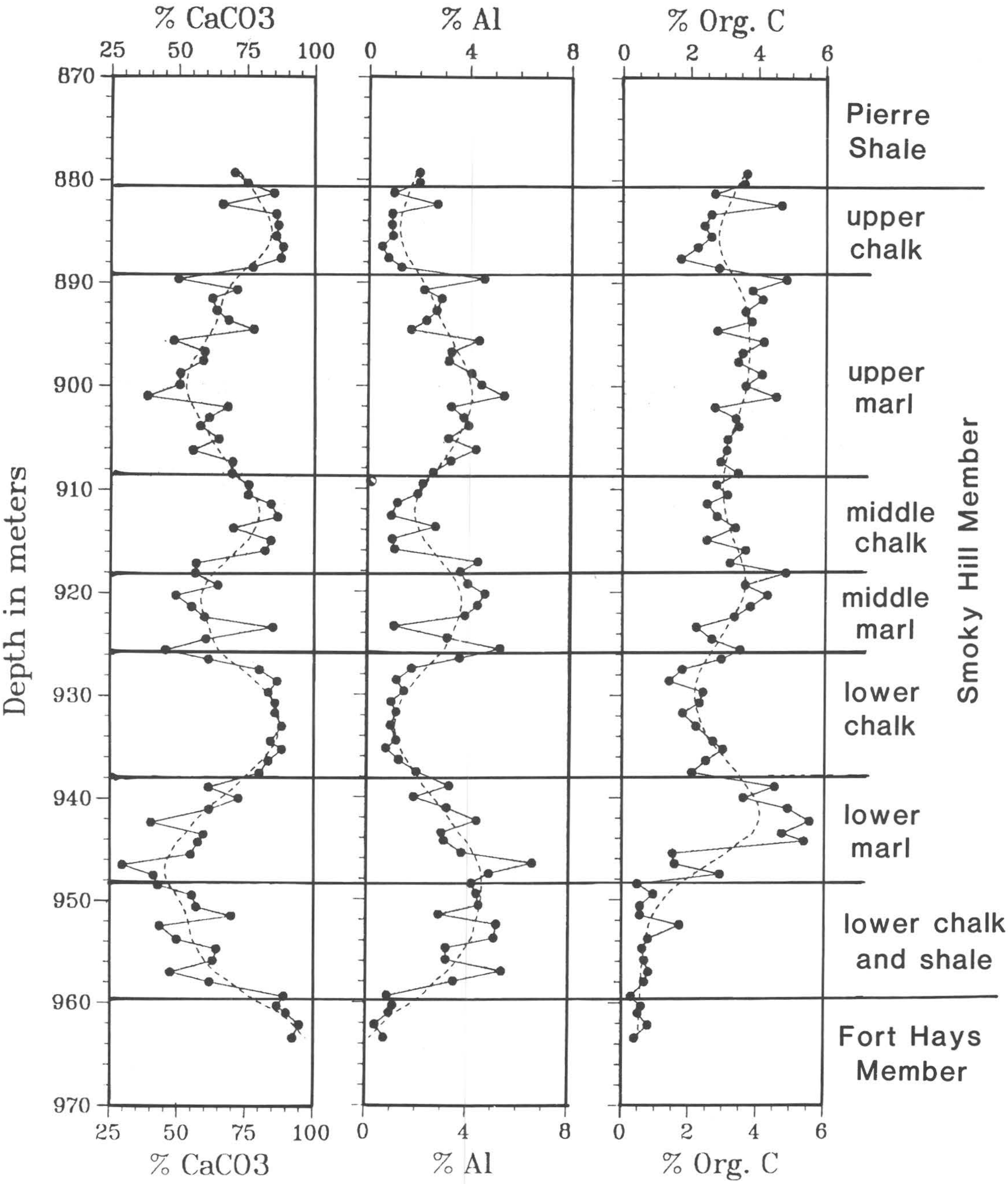


Figure 1. Geochemical logs of percent $CaCO_3$, aluminum (Al), and organic carbon (Org. C) for the Smoky Hill Member of the Niobrara Formation in the Coquina Oil, Berthoud State #4 well, Larimer County, Colorado. Dashed line through each log is a smoothed curve of the data computed using a spline smoothing function.

units, the Niobrara Formation and the Bridge Creek Limestone Member of the Greenhorn Formation. Although these two units are of minor stratigraphic significance compared to the thick siliciclastic sequences deposited during periods of lower sea level, they represent a major potential as petroleum source rocks.

Geochemical logs of cores of the Niobrara and Greenhorn from eastern Colorado show pronounced cycles whose periods range from tens of thousands to several million years. The longer-period cycles are illustrated for the Niobrara Formation (fig. 1) by logs of $CaCO_3$, aluminum (Al), and organic carbon (OC). The smoothed logs of $CaCO_3$ and Al (dashed lines in fig. 1) show distinct cycles on a scale of 30 m that correspond to the chalk and marl units of the Niobrara described in a 1964 study by G.R. Scott and W.A. Cobban. Within the 30-m cycles are sub-cycles that average about 5 m thick and show up in figure 1 as minima on the $CaCO_3$ log and maxima on the Al log within the marly units. The 5-m cycles also appear on down-hole sonic logs of the Niobrara Formation reflecting a greater degree of lithification of the limestone beds relative to the marlstone beds. The 30- and 5-m cycles can be seen in outcrop but are best observed in geochemical and geophysical logs.

The most visible cycles in cores and outcrops of both the Niobrara and Greenhorn are bedding cycles of limestone and marlstone that are several decimeters thick. The darker colored, marlstone beds contain more organic matter, higher concentrations of many trace elements, higher Sr:Ca ratios, and lower values of $\delta^{18}O$ than the limestone beds. The geochemical evidence confirms the importance of fluctuating freshwater runoff to the basin in producing changes in sediment supply and water column stratification, with consequent oxygen depletion and enhanced preservation of marine organic matter in the basin.

Although considerable uncertainty exists in the Cretaceous time scale, the periodicities of the bedding (decimeter) cycles in the Niobrara and Greenhorn and the 5-m and 30-m cycles in the Niobrara are estimated to be several tens of thousands of years, several hundreds of thousands of years, and several million years, respectively. G.K. Gilbert in 1895 was the first to suggest that the bedding cycles of the Niobrara and Greenhorn were related to global climate change driven by variations in the Earth's orbital characteristics, and that these cycles might be used to calibrate geologic time. Subsequently, the striking similarity of bedding cycles in many different marine carbonate sequences separated in space (global) and time (at least Mesozoic and Cenozoic), and the close correspondence of the estimated periodicities of some of these cycles to the Earth's orbital cycles (Milankovitch cycles) have been pointed out by numerous investigators. These cycles, therefore, may provide a stratigraphy of global and regional paleoceanographic events.

The pronounced rhythmic bedding of the carbonate units in the southern part of the western interior seaway resulted from climatic sensitivity of pelagic and hemipelagic depositional processes in that part of the basin, which was an arm of the northwestern margin of the Tethys ocean during maximum transgressions. It is the unique setting and climate sensitivity that has contributed to the periodic preservation of primarily marine organic matter, an unusual feature of pelagic carbonate facies. The enhanced preservation of organic matter occurred during periods of time when bottom-water masses were anoxic to slightly oxic as a result of increased water-column stabilization created by increased freshwater runoff into the basin. Organic carbon concentrations as high as 7 percent and pyrolysis hydrogen indices as high as 650 characterize some of the marly to shaly beds in each of the carbonate units indicating that both units have significant hydrocarbon generating potential. The northern and western parts of the seaway were shallower, more restricted, and less sensitive to climatic perturbations and, therefore, filled with more homogeneous clastic units.

Active Folding in the Hispaniola-Caicos Basin and Tectonic Control of Sediment Distribution Pathways from the Hispaniola Insular Margin

W.P. Dillon, K.M. Scanlon, N.T. Edgar, and L.M. Parson[1]

Ridges that trend at a shallow angle to the northern insular margin of the island of Hispaniola are disclosed by seismic-reflection profiles and GLORIA long-range sidescan-sonar imagery collected in the Hispaniola-Caicos Basin north of Haiti. Seismic profiles show that the ridges are anticlinal structures, having fold amplitudes that increase both downward and toward the insular margin. The lack of magnetic anomalies associated with the folds suggests that the structures, both in the deep basin and on the steep insular margin, do not involve basement. We conclude that here, at the boundary of the North American and Caribbean plates, the basin deposits are being progressively crumpled against the island block in the form of growth anticlines as a result of basin-floor movement west-southwest relative to the island of Hispaniola. Tightly folded and upraised basin deposits form the steep northern insular slope.

The sidescan imagery shows that the tectonic ridges extend diagonally away from the Haitian margin in a west-northwest direction. This ridge pattern creates parallel channelways that extend into the Hispaniola-Caicos Basin, and these channelways and interruptions present in the ridges seem to control the transport of sediment from the island of Hispaniola to the abyssal plain of the basin. One large fan debouches onto the floor of the basin from the end of a fold-controlled channelway off the central part of the northern Haiti insular margin.

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A Rationale for the Method of Estimating the Number of Small Undiscovered Oil and Gas Fields

L.J. Drew, J.H. Schuenemeyer, and E.D. Attanasi

Our study provides a rationale for the method of estimating the number of small oil and gas fields remaining to be discovered in partially explored regions. In these regions, small fields contain most of the undiscovered conventional oil and gas resources. Our rationale is that (1) the underlying field size distribution is log-geometric in form, and (2) the apparent declining frequency in the smaller size classes is a consequence of an economic filtering or truncation process.

This rationale has been developed and tested using data from the Minnelusa and Frio plays, the Texas State and Federal waters, the western Gulf of Mexico offshore, the Denver and Permian basins, the North Sea, and world offshore. From analyses performed in these nine exploration plays, basins, and larger areas, we have demonstrated that the observed relative frequency of fields in the smaller size classes is directly related to the cost of discovery and of developing oil and gas fields. Moreover, further study of several of these basins showed that the mode of the observed field size distribution shifted to smaller size classes when oil and gas prices increased.

A discovery process model was used in conjunction with the log-geometric assumption to estimate a factor, *r*. This factor represents a multiplier such that the ultimate number of fields in each size class has *r* times the number of fields in the next size class larger. This factor was computed using the estimated ultimate number of fields from those field size classes thought to be unaffected by economic truncation. In size classes unaffected by economic truncation, the discovery process model was used to predict the ultimate number of fields which occur. The resulting *r*-factor was then applied to the field size classes affected by economic truncation to estimate the number of fields occurring in these size classes.

GLORIA Sonographic Mosaics of the Bering Sea and the Western Aleutian Arc and Adjacent North Pacific

EEZ-Scan Bering Sea[1] and Aleutian Arc[2] Groups

Since 1984 the U.S. Geological Survey has cooperated with the Institute of Oceanographic Sciences (U.K.) to survey the Exclusive Economic Zone (EEZ) of the United States. The principal mapping tool is the GLORIA system, a long-range sonar. Bathymetry, high-resolution seismic-reflection, dual-channel air-gun, gravitational and magnetic field data are collected in addition to the wide-swath sonar. Among the geologic settings investigated during the 4 years of the project is the Bering Sea–Aleutian arc region, a sedimentologically and tectonically complex area of plate convergence. Three cruises in 1986 and one cruise in 1987 surveyed about 850,000 km^2 of the EEZ in the Bering Sea from Unimak Pass northwest to the U.S.-U.S.S.R. Convention Line of 1867. Two cruises in 1987 surveyed about 400,000 km^2 of the western Aleutian arc and trench and adjacent North Pacific seafloor from Adak Island westward to the 1867 Convention Line and from the 200–m isobath seaward 375 km (200 n.m.) to the boundary of the U.S. EEZ.

Some of the largest submarine canyons in the world incise the Beringian margin. These canyons, particularly Navarinsky, Pervenents, and Zhemchug, have been excavated principally by mass wasting. The products of mass transport range from small slides and slumps less than 1 km^2 in area to slides of several hundred square kilometers. No large channels extend onto the basin floor from the mouths of the canyons along the Beringian margin northwest of Bering Canyon, which suggests that those canyons contribute only small amounts of modern sediment to the Aleutian Basin. Three channels that issue from Bering, Umnak, and Pochnoi canyons are the primary conduits through which sediment is dispersed to the abyssal floor of the Aleutian Basin. The extent of these channels, which cross the abyssal seafloor for several hundred kilometers, was unknown prior to the GLORIA survey. Bering channel, the most prominent, feeds sediment to the Bering fan, which is characterized by a complex acoustic backscatter pattern. The other channels also transport sediment to this area, which appears to be the primary locus of modern deposition in the southeastern part of the Aleutian Basin.

Large amounts of sediment are shed to the basin floor from the Aleutian and Bowers Ridges. The erosion of these ridges is being expedited by tectonic uplift leading to unstable, oversteepened slopes. The apparent youthfulness of seafloor scarps, submarine volcanoes, and basement ridges beneath the crest and flanks of Bowers Ridge suggests that Bowers Ridge is presently being uplifted as well as eroded. In contrast, the abyssal basin areas of the Bowers Basin and southwestern

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[2]R.G. Bohannon, B.D. Edwards, H.A. Karl, T.L. Vallier (USGS); M.F. Dobson (University of Wales at Aberystwyth); and D. Masson (I.O.S., Wormley, U.K.).

Aleutian Basin appear to be tectonically stable and receiving mostly pelagic sediments.

The seafloor morphology and the geology south of the Aleutian arc are dominated by subduction tectonics. Structurally controlled submarine canyons head on the shelf summit arc platform, but do not debouch onto the floor of the Aleutian trench; instead they terminate in forearc basins that are filled with thick sediment accumulations. Subtle pathways of sediment dispersal are seen on the sonographs where sediment has spilled over from sediment-filled forearc basins onto the trench floor. A small canyon that has developed on the accretionary wedge south of Amchitka Island, possibly by mass wasting, shows an active channel that appears to be feeding a fan on the trench floor. Tectonic elements within and near the subduction complex include a flat trench floor, landward-verging thrusts in the accretionary prism, and faults on the seaward slope of the trench that are oriented subparallel to the direction of plate convergence. Stalemate ridge, a small piece of Kula plate, and the extinct Kula-Pacific ridge are tectonic elements of particular interest on the North Pacific seafloor. Collision of the Stalemate ridge (extinct Kula-Pacific transform fault) with the arc margin has caused extreme deformation of the forearc that includes, for example, uplift of the trench floor of more than 500 m relative to other parts of the trench.

Available Coal Resources—A Pilot Study

Jane R. Eggleston, M. Devereux Carter, and James C. Cobb[1]

According to the Energy Information Administration of the U.S. Department of Energy, the United States currently has more than 400 billion tons of coal in the Demonstrated Reserve Base. The reserve base includes coal that is available for mining, and its estimate is determined by applying designated bed thicknesses, mining depths, and reliability factors to a geologically derived coal-resource data base. However, this methodology for estimating coal available for mining ignores many geologic, environmental, engineering, and economic factors that further restrict the availability of minable coal. When these additional factors are considered, the amount of coal actually available for mining may be significantly reduced. Although attempts have been made to define available coal, none have used a comprehensive, point-source, geologic data base and incorporated all the geologic, land-use, cultural, and engineering restrictions currently placed on the mining of coal.

To quantify these restrictions and to determine their impact on available coal resources, a pilot study in the Appalachian region has been initiated by the U.S. Geological Survey in cooperation with the Kentucky Geological Survey. The Matewan 7½-minute quadrangle, Pike County, eastern Kentucky, was selected for the pilot study. Factors that limit the availability of coal for surface and underground mining, defined as restrictions, were compiled at 1:24,000 scale. The U.S. Geological Survey's National Coal Resources Data System (NCRDS) was used to assemble and manage the data base for all geologic and mining data. For surface mining, environment-related restrictions are surface features that are immovable and that generally must have barriers left around them. These restrictions include: (1) major powerlines and pipelines, (2) towns and public buildings, (3) federal highways, (4) cemeteries, (5) oil and gas wells, (6) railroads, and (7) environmentally sensitive areas, such as endangered species habitats, protected rivers, game lands, lakes, and parks. In addition, surface mining is restricted by the limiting strip ratio that can be achieved and still be economic. Restrictions on underground mining are primarily economic and technologic. A coal bed will not be mined if: (1) it is either too shallow or too deep; (2) it is within a certain distance above or below an active/abandoned mine or coal bed which is more likely to be mined; (3) it is located in highly folded or faulted areas; (4) roof or floor conditions would be too problematical; and (5) the coal bed is too thin to be mined by conventional technology. Coal quality may be a restricting factor if the coal does not meet compliance standards for sulfur or if it does not meet user specifications.

All these factors were entered into NCRDS and applied to the remaining coal resource estimate for the Matewan quadrangle to derive the available coal resource estimate. Initial investigations on the Upper Elkhorn No. 2 coal indicate that of the 106 million short tons of original coal resources, 92 million short tons now remain after mining, and only 28 million short tons, or 30 percent of the remaining coal, is actually available for mining. If other factors such as percent recovery and mining economics are considered, available coal is further reduced.

The data for the Matewan quadrangle may be extrapolated some distance, but only as far as the geologic, environmental, engineering, and economic conditions remain relatively uniform. Additional studies are required to determine if the results for this quadrangle are representative of other areas of the Appalachian basin.

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Basin Evolution and Upper Paleozoic Coal Deposits in the Central Appalachian Basin

Kenneth J. Englund and Roger E. Thomas

The distribution and character of upper Paleozoic coal beds in the central Appalachian basin were influenced by a series of terrestrial depositional events associated with basin evolution. Most sediment originated as siliciclastic detritus eroded from tectonic highlands that were elevated by plate collision along the southeastern margin of the basin. Deposition occurred in a slowly subsiding foreland basin occupied mostly by northwestward-prograding delta lobes and, to the northwest, on an unstable cratonic shelf covered by a shallow epicontinental sea. A transition from terrestrial to marine deposition is recorded by time-equivalent sequences of coal and related swamp accumulations, fluvial and deltaic sandstone, lagoonal and bay-fill shale, barrier- and offshore-bar sandstone, and marine shale and limestone. Terrestrial progradation was dominant during periods of high rainfall and sufficient subsidence to accommodate the influx of sediments. Conversely, marine incursions extended farthest southeastward during periods of diminishing rainfall and minimal sediment influx. When the shift from regression to transgression was gradual and near equilibrium existed between marine and terrestrial influences, stillstands of sea level coincided with widespread peat accumulations and barrier- and offshore bar development. As the Appalachian basin evolved, the shoreline or wedge-out of terrestrial deposition shifted gradually northwestward and rotated from N. 30° E. in Early Mississippian time to N. 65° E. in Early Pennsylvanian time (fig. 1). This change in the sedimentary trend coincided with a similar rotation in the deformational strike of the faulted and folded Appalachians which may have resulted from plate rotation during collision. Coal bed characteristics including rank, ash and sulfur contents, and selected trace elements in coal ash also exhibit trends that can be related to basin evolution.

Analcime in Coal Beds of the Wasatch Plateau, Utah—Geological and Technological Significance

Robert B. Finkelman

Sodium is generally believed to be a major contributor to fouling and corrosion of coal-fired boilers and to agglomeraton in fluidized-bed combustors. Most sodium in coal beds is also generally believed to be in either (1) ion-exchange sites in organic matter or in clay minerals, or (2) solution.

A recent study of 27 samples from Upper Cretaceous coal beds of the Wasatch Plateau, Utah, reveals that much of the sodium in these beds occurs in an unusual mode—as analcime, a hydrous sodium aluminum silicate. Analcime was detected in 23 of the 27 samples. In the high-sodium coal beds in the central and southern parts of the plateau, as much as 90 percent of the sodium is present as analcime. The analcime occurs primarily as fracture fillings in the coal beds and, to a lesser extent, as cell fillings in coal macerals of the inertinite group.

The unusual mode of occurrence of sodium in the Wasatch Plateau coal beds has potentially important consequences.

- Awareness of the structural, hydrologic, geologic, and geochemical controls on analcime distribution should help in developing an exploration strategy for low-sodium coal. The textural evidence indicates that analcime in the coal is clearly of secondary origin. Analytical data from local water samples were tested using a chemical equilibrium modeling program to determine the source of the analcime. The results indicate that the analcime and the associated epigenetic minerals (calcite and pyrite) could have precipitated from water from the underlying aquifer, the Ferron Sandstone Member of the Mancos Shale. The higher sodium concentrations in the plateau coal beds occur along the trace of the synclinal axes in the Ferron between the Pleasant Valley and Joes Valley fault systems. It is likely that the distribution of analcime (and therefore of sodium) was controlled by the fault pattern and the potentiometric surface of the Ferron aquifer.
- Sodium occurring in a *mineralogical* form such as analcime is not as likely to contribute to boiler fouling as much as *organically associated* sodium. This may explain why the Wasatch Plateau coals, even with relatively high sodium content, are not known to cause boiler fouling.
- Because of the unusual mode of occurrence of sodium in coal beds of the Wasatch Plateau, the various empirical fouling indices are not applicable. These indices assume that sodium in coal is in a volatile form.
- It will be possible to use weathered samples of coal for evaluation of the sodium distribution in areas of the plateau where fresh samples are unavailable. Examination of samples from deeply weathered outcrops of coal revealed the presence of relict analcime as well as the residual and weathering products (quartz and kaolinite).
- It appears that conventional coal-cleaning procedures could effectively remove sodium (as well as much of the ash) from this coal. A laboratory density separation removed approximately one-half of the anal-

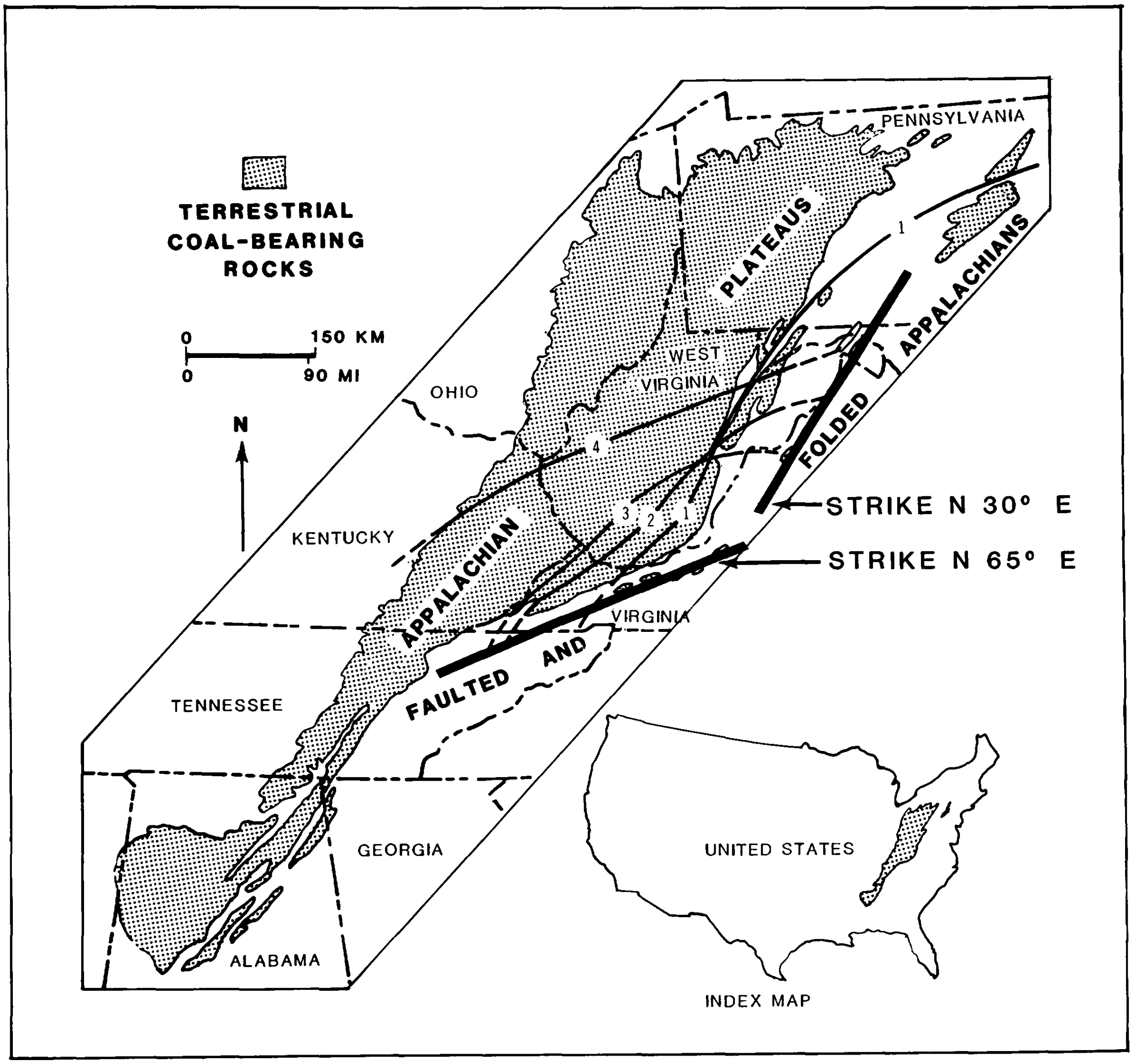

Figure 1. Map of the Appalachian basin showing the northwestward wedge-out of terrestrial coal-bearing rocks in the Price (1), Bluestone (2), Pocahontas (3), and New River (4) Formations or correlatives and the relation of sedimentation trends to the strike of major structural trends of the faulted and folded Appalachians (heavy lines). Dashed formation line, extension beyond control.

cime with a concomitant loss of less than 10 percent of the coal. Perhaps the resultant analcime-rich concentrate could itself be marketed for one of the many purposes for which zeolite minerals are commercially used.

- Because analcime is not preferentially concentrated within a particular coal bed, selective mining techniques to reduce sodium content will not be effective.

- Mining of coal and leaching of coal in stockpiles should not significantly contribute to the deterioration of surface-water or ground-water quality through the release of sodium, because sodium in these coals occurs largely in a non-water-soluble mineral form.

Offshore Resource Geology of Selected South Pacific Island Nations—The USGS SOPAC Program

H. Gary Greene, Michael S. Marlow, David W. Scholl, and John G. Vedder

The USGS's geoscientific program in the Southwest Pacific (SOPAC) is coming to an end in 1988 after 5 years of intensive marine geophysical investigations in the waters of Papua New Guinea (PNG), Solomon Islands, Vanuatu, and Tonga. The data collected in these regions during the 7 months of surveying by the *S.P. Lee* consist of 24-channel CDP, single-channel airgun, Uniboom, and 3.5-kHz seismic-reflection profiles; sonobuoy wide-angle seismic reflection/refraction; and gravity and magnetic profiles. These data, as well as seafloor photographs, sediment samples, and rock samples, were used to assess the hydrocarbon potential of this region.

Thick sequences of sediment mapped throughout the region range from approximately 3 km thick on the southern Tonga platform to as much as 8 km thick in the Queen Emma Basin of eastern PNG. Sediment thickness increases from south to north along the active island arcs of Tonga, New Hebrides, and Solomon Islands. The thickest and most extensive sedimentary units underlie the intra-arc basins of Vanuatu, Solomon Islands, and eastern PNG. These basins resulted from complex Neogene tectonic events that include subduction, subduction polarity reversal, and oblique ridge-arc collisional events. These tectonic processes induced wrench-faulting, with associated horsts and basin-forming grabens. Thick deposits of eroded carbonate and volcaniclastic sediment from adjoining islands, as well as pelagic material, accumulated in the grabens.

Oil seeps reported in Tonga, Fiji, and Vanuatu indicate that hydrocarbons have been generated in these regions. Onshore source-rock analyses suggest only a remote potential for the generation of gas, and none for oil. Drilling both onshore and offshore in Tonga and Fiji has not recovered hydrocarbons. However, reevaluation of old geophysical data along with the interpretation of the new USGS data has shown new targets. For example, buried reefs have been located in offshore Tonga, and structural traps occur along the basin flanks in Vanuatu, Solomon Islands, and PNG. A "bright spot" or acoustical geophysical anomaly was discovered in New Ireland Basin, PNG, suggesting hydrocarbons trapped within the basin. Much more work needs to be done in these regions to fully understand the energy and mineral resources.

Laramide Thrusting of the Bighorn Mountains onto the Powder River Basin near Buffalo, Wyoming

J.A. Grow, E.N. Hinrichs, J.J. Miller, M.W. Lee, and S.L. Robbins

Recent seismic surveys and exploratory drilling by industry for subthrust oil and gas prospects beneath the Bighorn Mountain front along the western edge of the Powder River Basin near Buffalo, Wyoming, reveal a basement-involved thrust of considerable magnitude. A deep test for oil and gas, the Arco 1–4 Kinney Ranch borehole, was drilled 13 km (8 mi) west of Buffalo and penetrated 750 m (2,460 ft) of Precambrian granite gneiss before penetrating the thrust and entering 1,475 m (4,838 ft) of the Paleocene Fort Union Formation and another 2,199 m (7,212 ft) of Mesozoic and Paleozoic sedimentary rocks. The Gulf Granite Ridge 1–9–2D borehole, which was drilled 31 km (19 mi) north-northwest of the ARCO borehole and 5 km (3 mi) northwest of Story, Wyoming, penetrated 1,768 m (5,800 ft) of granite before entering Upper Cretaceous strata. This borehole penetrated a total of 3,021 m (9,910 ft) of Mesozoic and Paleozoic sedimentary rocks.

Chevron U.S.A., Inc. supplied to the USGS two very high quality seismic reflection profiles near the Kinney Ranch and Granite Ridge boreholes. These profiles have been reprocessed by the USGS and integrated with surface geologic mapping, gravity surveys, and other geologic studies by the USGS in progress in the Powder River Basin. The seismic profiles near the Kinney Ranch and Granite Ridge boreholes clearly show that sedimentary rocks of Paleozoic through Paleocene age, which occur beneath the thrust fault, extend more than 11 km (7 mi) westward from the eastern edge of the basement thrust. The fault plane at the base of the Precambrian granites and gneisses dips 30° to the west. Although exploration for oil and gas plays beneath basement overthrusts along the Bighorn Mountain front has not been successful to date (fall 1987), information derived from this effort provides valuable insight into the tectonic processes along Laramide overthrust zones and the techniques required for future exploration.

Organic Geochemical Studies of the Early Coalification of Peat and Associated Xylem Tissue

Patrick G. Hatcher, Harry E. Lerch III, T.V. Verheyen[1], and M.A. Wilson[2]

Organic geochemical investigations of peat, coal, and associated xylem tissue from both gymnosperms and angiosperms have provided useful information on the organic transformation processes collectively known as coalification. The combined use of solid-state ^{13}C nuclear magnetic resonance (NMR) and pyrolysis/gas chromatography/mass spectrometry (py/gc/ms) allowed us to examine the organic composition of these materials, on both a bulk (average) compositional and a detailed molecular basis. From the study of angiosperm and gymnosperm xylem we conclude that coalification

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[2]Commonwealth Scientific and Industrial Research Organization, North Ryde, NSW, Australia.

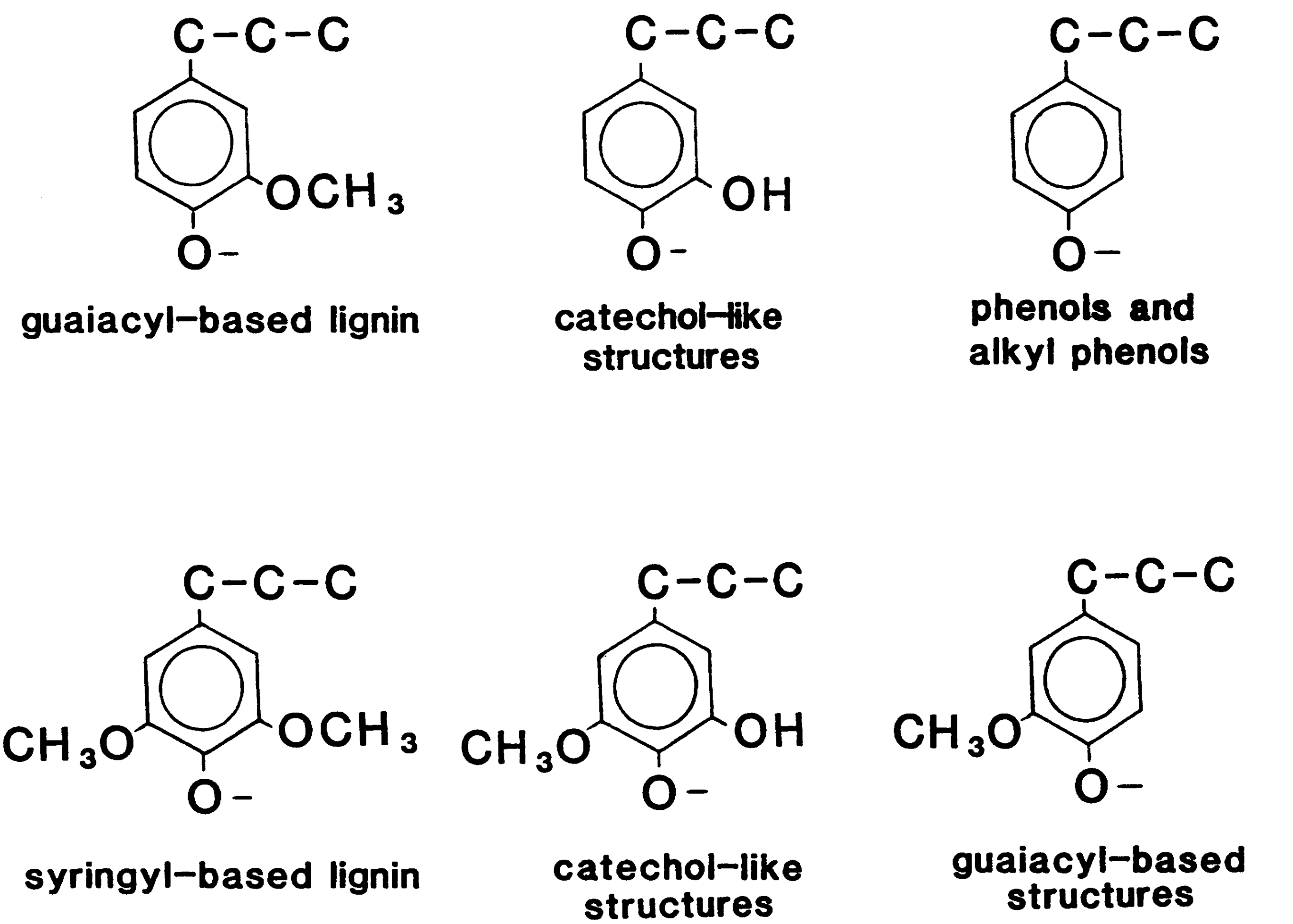

Figure 1. Proposed coalification pathways for lignin.

involves the following processes:

1. Early selective removal of cellulose so that lignin, the primary constituent of xylem, in turn becomes the macromolecular aromatic components in coal.
2. Modification of both angiosperm and gymnosperm lignin by demethylation reactions to form catechol-like structures (fig. 1). In angiosperms, the syringyl-based lignin is more rapidly transformed than the guaiacyl-based lignin. Eventually, the aromatic angiosperm residues begin to resemble those of coalified gymnosperm wood, which is primarily derived from guaiacyl-based lignin.
3. With increasing coalification to subbituminous coal, the resultant xylem becomes selectively enriched in specific phenols and alkylphenols as the catechol-like structures decrease, indicating a dehydroxylation process.

In our studies of coal and its precursor, peat, the coalification of xylem tissue only partly explains the overall transformation. Other substances such as degraded algae, bark, leaf material, oxidized wood, and other plant remains can be recognized as chemically contributing to the organic composition of our peat and coal samples. The chemistry of such contributors and the processes by which these components become coalified are complex and not well known. However, one process that appears universal to nearly all chemically altered plant remains is the degradation and loss of carbohydrates. Another process that can be discerned is the selective degradation of aromatic components relative to aliphatic components (such as resins, waxes, and cuticles). The extent of degradation is partially dependent on the degree of oxidation of the peat. Thus, changes in aromaticity within a coal bed may reflect differences in source contributions and (or) differences in degree of oxidative degradation. The latter process, if quantifiable, may aid in identifying facies variations within coal beds.

Phosphorus Burial in the Deep Sea During the Past 125 Million Years

James R. Herring, Walter E. Dean, and Michael A. Arthur[1]

Much of the effort applied to the study of commercial-grade sedimentary phosphate deposits has been with the hope that the temporal and spatial record of these deposits would provide clues assisting the search for new deposits. Inventories have been made of phosphatic deposits through time searching for periodicities, common environments, or depositional mechanisms. These inventories focus only on the enriched phosphatic deposits and ignore the lesser concentrations of organic phosphorus (P_{org}) in deep-sea sediments, although the enormous volume of deep-sea sediments suggests that this reservoir of P_{org} might be important to the overall global phosphate cycle and, hence, to the occurrence of enriched deposits. Estimates of phosphate burial in the deep sea have been difficult to obtain because the ubiquitous and often dominant inorganic phosphorus component in crustal rocks cannot be differentiated from the P_{org} content. However, we have devised a method to determine the inorganic phosphorus content of these pelagic sediments; thus we are able to calculate P_{org} contents.

In order to differentiate the rate of burial of P_{org} from that of total phosphorus (P_{tot}) we have used the aluminum-P_{tot} ratios for several localities throughout the Atlantic and Pacific Oceans, each chosen to represent one of three types of depositional environments for the inorganic contribution to marine sediments: terrigenous, hemipelagic, and eolian. A plot of the Al:P_{tot} ratio allows us to estimate the contribution of inorganic phosphorus, which then is subtracted from the P_{tot} concentration and leaves the fraction of the phosphatic material resulting from biogenic processes (P_{org}). Our inventory of sedimentary P_{org} for Cenozoic and Upper Cretaceous deep-sea sediments is several hundred times larger than published inventories of commercial phosphatic deposits over this same interval, indicating that the P_{org} content of deep-sea sediments indeed is a major part of the global sedimentary phosphate cycle. Only subtle changes in the P_{org} content incorporated in deep-sea sediments through time would be necessary to produce the amounts of phosphate that occur in typical, large commercial deposits, for example those of western Africa or the southeastern United States. This phosphate then would need to accumulate in a local environment favorable for phosphatic enrichment, deposition, and preservation.

We also have examined relationships among Al, organic carbon (C_{org}) and P_{tot} in Cretaceous and Tertiary deep-sea sediments. A ternary diagram of weight percent concentrations of Al, C_{org} and total phosphorus × 100 (P_{tot} × 100) provides a convenient way of examining relationships among these three variables in C_{org}-rich sediments. An Al:P_{tot} × 100 ratio of about 1:1 represents the crustal average, and this line on a ternary diagram provides a convenient reference for measuring phosphate enrichment or depletion relative to the crustal concentration. A C_{org}:P_{tot} × 100 ratio of about 1:1 represents the Redfield ratio of these two elements in living organic matter. Oxidative decay of organic matter usually results in a progressive loss of P_{org} relative to C_{org}, which increases the C_{org}:P ratio. Most Cretaceous C_{org}-rich strata recovered from Atlantic DSDP sites show what is essentially dilution of terrigenous detritus with C_{org} and a slight enrichment in P_{tot}. Most sample sets show considerable variation in the C_{org}:P ratio with both enrichment and depletion in P_{tot} relative to the Redfield ratio.

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Burial History Reconstruction of the Lower Cretaceous J Sandstone in the Wattenberg Field, Colorado, "Hot Spot"

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A Wattenberg Field thermal anomaly or "hot spot" is recognized by analysis of present-day geothermal gradient and thermal maturity data from the Denver basin. Thermal maturity was determined in the Wattenberg Field and across the basin by sampling and analyzing the Lower Cretaceous J sandstone and adjacent hydrocarbon source rocks for percent mean random vitrinite reflectance (R_m). The degree of source rock thermal maturity is primarily affected by burial depth, with resultant thermal and diagenetic effects. The highest R_m values occur north of the structurally deepest part of the Denver basin, in the Wattenberg Field of southwestern Weld County. Comparison of R_m data to burial depth throughout the Denver basin indicates that the "hot spot" has anomalously high R_m values, ranging from 1.05 to 1.51 percent at current depths of 7,000 to 8,000 ft.

TTI burial history analysis was used to characterize the J sandstone thermal history both within and outside the Wattenberg Field. Burial history reconstructions of coreholes within the "hot spot" used the present-day geothermal gradient range of 2.0–2.9 °F/100 ft, considerably higher than the 1.6–2.0 °F/100 ft present in most of the Denver basin.

Outside the "hot spot," calculated TTI's correlate to present-day R_m data for the J sandstone, suggesting that most of the Denver basin experienced only minor heat flow fluctuations from Albian to the present. Assuming current geothermal gradients were present from the time of J sandstone deposition, the Wattenberg Field has anomalously high TTI's compared to R_m values.

The burial history of the #1 G.W. Steiber Unit Amoco well, SW SW 24, T. 1 N., R. 67 W., was calculated with the present-day geothermal gradient of 2.55 °F/100 ft and an assumption of 2,550 ft of eroded sediment, most of which eroded from Miocene time to the present. The calculated 687 TTI is approximately equivalent to an R_m of 1.9 percent. The measured R_m is considerably lower at 1.14 percent, indicating that the J sandstone in this corehole was subjected to lower heat flows in the past, resulting in a lower thermal maturity level than is indicated with the current geothermal gradient.

The Wattenberg Field lies along a series of northeast-trending basement lineaments that define the Colorado Mineral Belt. Activation of these basement structures, especially during and after the Laramide orogeny, may have influenced the heating history of overlying sediments by increased heat input and through more efficient heat flow along associated faults and fractures. Wattenberg Field burial history reconstructions that assume a lower geothermal gradient prior to the Laramide orogeny, about 68 million years ago, result in a closer correlation of TTI to measured R_m data and indicate that the Wattenberg Field area was subjected to lower geothermal gradients in the past.

Faulting and Folding on the Eastern Flank of the Bighorn Mountains, Sheridan and Johnson Counties, Wyoming

E. Neal Hinrichs

Recent information from seismic surveys, boreholes, and geologic mapping has clarified the structure of the eastern flank of the Bighorn Mountains in Sheridan and Johnson Counties, Wyoming, especially the subsurface extent of basement-involved thrust faults. These mountains in north-central Wyoming trend north-northwest near the eastern edge of the Rocky Mountain foreland and separate the Bighorn and Powder River Basins.

The core of this range consists of Precambrian igneous and metamorphic rocks, chiefly granitic rocks of Middle and Late Archean age (2,900–3,200 Ma), and dikes and plugs of mafic and ultramafic rocks of Late Archean age (2,600–2,800 Ma). The structural grain of the Precambrian rocks trends generally northeast, parallel to the grain at the southern edge of the Powder River Basin. Surrounding the core are sedimentary rocks of Cambrian to Oligocene age totalling about 5 km thick. Those best exposed are the Ordovician Bighorn Dolomite, the Mississippian Madison Limestone, and the Pennsylvanian Tensleep Sandstone.

The Bighorn Mountains can be divided into three structural blocks, northern, southern, and central, on the basis of directions of structural movement. The northern and southern blocks were transported southwestward, as indicated by pairs of folds overturned to the southwest and by eastward-dipping, high-angle reverse faults. The central block, however, displays evidence of transport to the east-northeast over a thrust fault that dips 30° to the west. This central block is approximately 28 miles in the north-south dimension and consists of the Piney lobe, Mowry Basin, and the Johnson Creek–Crazy Woman Creek segment. Primary thrust faults and secondary strike-slip faults, many of which involve Precambrian rocks, cut the central block. A large thrust fault under the Piney lobe shows clearly on a seismic profile (courtesy of Chevron U.S.A., Inc.) that extends southwest from the town of Big Horn past a borehole at Granite Ridge to Penrose Park. A thrust fault in the Johnson Creek–Crazy Woman Creek segment is represented on a second seismic profile that extends east along French Creek about a mile north of the borehole at Kinney Ranch. The thrust faults in the central block are offset by strike-slip and normal faults, some of which are extensions of reactivated Precambrian faults. One of these extensions has right lateral displacement and extends southwestward into a dike of diabase and diorite.

In comparison to the Piney lobe and the Johnson Creek–Crazy Woman Creek segment, the Mowry Basin is a topographic low over a structural high. The top of the Tensleep Sandstone in the Reasor 1 Tarbet borehole, in the southern part of Mowry Basin, is about 2,500 ft higher than in the borehole at Granite Ridge and about 1,500 ft higher than in the borehole on Kinney Ranch. Uplift along east-west faults is probably the main cause of the structural high. Several visible faults separate Mowry Basin from the rest of the central block. Some of the uplift probably was caused by concealed faults, including the Buffalo Deep fault, a major reverse fault that trends northwest between the Tarbet and Granite Ridge boreholes. The petroleum potential of Mowry Basin is a function not only of structurally high reservoir rocks, but also of hydraulic connection to source beds, mainly Cretaceous marine shales beneath the thrust fault. This connection may have been severed by numerous faults which may also have contributed to reduction in porosity. Knowledge of the tectonic history gained through geologic mapping, subsurface drilling, and geophysical data is essential in the assessment of exploration targets along complex compressional mountain fronts such as the Bighorns.

The tectonic history of the area during the Laramide orogeny began with uplift of the Bighorn Mountains and (or) subsidence of the Powder River Basin, late in the Paleocene Epoch. The resultant syntectonic conglomerates in the upper part of the Fort Union Formation and the lower part of the Wasatch Formation were deposited along the eastern front of the mountains. Near the end of the Eocene Epoch, regional east-west compression caused thrust and strike-slip faulting that delineated the three structural blocks in the Bighorn Mountains.

Supergene Enrichment of Sulfur in Coal Deposits of the Powder River Basin

Charles W. Holmes and Anthony B. Gibbons

The lower Tertiary of the Powder River Basin, northeastern Wyoming, consists of terrestrial siltstones, sandstones, and coals of the Paleocene Fort Union and the Paleocene and Eocene Wasatch Formations. The thick coals are considered to be of high quality as they are generally low in sulfur; however, some zones of high sulfur (>4.0 percent) are present in the basin. The sulfur content of coals from the Wasatch Formation ranges from 0.3 to 6.4 percent; the sulfur content of coals from the Fort Union Formation ranges from 0.1 to 5.2 percent.

Samples of coal and associated strata collected from drill holes in the Powder River Basin show that the total sulfur distribution in the subsurface defines three distinct zones. In rocks within approximately 15 m of the surface, sulfur content ranges from 0.1 to 0.25 percent. At depths between 15 m and 45 m, the sulfur content of the rocks increases to levels between 1.0 and 5.5 percent. Below 45 m sulfur contents decrease slightly to range between 0.75 and 1.25 percent. The boundaries of these zones follow the local topography, and cut across the westward-dipping strata. Coal beds intersecting the enriched zone show a definite localized increase in sulfur content within the zone.

Most of the sulfur in the surface zone occurs as sulfate in the mineral gypsum. In the intermediate enriched zone and in the lower reduced zone, sulfur occurs as a sulfide primarily as pyrite. The distribution of sulfur isotopes ranges from -7.5 $\delta^{34}S$ (CDT) in the surface zone to +2.1 $\delta^{34}S$ (CDT) in the enriched zone. This evidence indicates that much of the sulfur in the enriched zone was derived from the overlying oxidized zone. The sulfur enrichment thus appears to result from geochemical processes similar to those that form roll-front uranium or supergene metal deposits. Oxidizing meteoric waters migrating downward through the sediments carry dissolved sulfur species to lower depths where reduction reactions predominate. Here the sulfur forms sulfides and over time accumulates to form a sulfur-enriched zone. If this zone intersects coal, the elevated chemical potential present in the organic material of the bed would tend to enhance the sulfur concentration over that of the adjacent non-organic rocks.

Santa Maria Project, Central California Coast

C.M. Isaacs and R.G. Stanley

The Santa Maria Project, jointly undertaken under the U.S. Geological Survey's Evolution of Sedimentary Basins Program and the Onshore Oil and Gas Investigations Program, focuses on the tectonically active south-central California continental margin. The study covers the onshore region west of the Sur-Nacimiento fault and north of the Santa Barbara Channel together with adjacent offshore areas, a region embracing the onshore Santa Maria basin proper, offshore Santa Maria basin, Pismo basin, Huasna basin, and several other small basins and basin fragments. The Santa Maria province contains the world's largest diatomite deposit as well as major deposits of petroleum (>1 billion bbl), tar sand, heavy oil, and oil shale. The province also includes the most extensive fractured petroleum reservoirs in California and, in the offshore, the largest United States petroleum discoveries since Prudhoe Bay.

The Santa Maria province has had a complex tectonic history. Mesozoic and lower Paleogene rocks form a collage of tectonostratigraphic terranes that apparently accreted to the North American continent by late Eocene time. Many questions remain about the sites of origin of the terranes, their travel paths, and the processes and timing of terrane suturing and continental "docking." Overlying pre-Eocene strata and fragments of Eocene marine and Oligocene-Miocene nonmarine clastic strata are deposits in numerous economically important basins, which began to form along the continental margin at about the Oligocene-Miocene boundary. Miocene to Pleistocene strata deposited in these basins include clastic marine and nonmarine strata, minor volcanics, and the organic-rich biogenous strata of the Miocene Monterey Formation, the source of diatomite and petroleum deposits. The origin of the Neogene basins is controversial; wrench tectonism, regional extension, and large-scale block rotation are among proposed mechanisms. Differences among models are so great that Miocene paleolocations, onshore-offshore orientations, and basin geographies are completely uncertain. However, Miocene facies and their subsequent structural, thermal, and compaction history critically controlled petroleum generation and reservoir formation.

Major geologic problems addressed by the project are thus: (1) the origin and timing of terrane accretion; (2) the origin and history of the Neogene sedimentary basins; (3) Miocene paleogeography and lateral facies variations; and (4) the thermal and structural history of the province. Excellent surface exposures occur on the province peripheries and extensive subsurface data are available from both onshore and offshore. Thus the Santa Maria province offers an uncommon opportunity to resolve major tectonic and paleogeographic problems of wide interest and broad application.

Initial studies in the Santa Maria Project will focus on the stratigraphic and structural framework, with particular emphasis on detailed mapping in key areas and intensive study of important stratigraphic sections in outcrops and wells. Specific projects underway or planned include: (1) mapping in the Lopez Mountain and Point Arguello areas; (2) detailed sedimentologic and biostratigraphic study of Oligocene-Miocene nonmarine and marine strata; (3) comprehensive dating of Miocene volcanic units; and (4) thermal history studies of lower Neogene sandstones. In addition, the following regional summaries are underway: (1) major cross sections based on outcrop, subsurface, and geophysical data; (2) compilations of the geology, gravity, and magnetics; (3) a series of paleogeographic compilations illustrating the geologic evolution of the province from Jurassic to Holocene; and (4) a synthesis of the basin's geologic evolution from Jurassic to Holocene.

An Assessment of Gas Resources in Low-Permeability Sandstones of the Upper Cretaceous Mesaverde Group, Piceance Basin, Colorado

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Prepared in cooperation with the U.S. Department of Energy, Morgantown, W.Va.

A modified volumetric approach was used to estimate in-place and recoverable gas resources in the low-permeability sandstones of the Upper Cretaceous Mesaverde Group in the Piceance basin of western Colorado. For the analysis the Mesaverde Group was subdivided into three stratigraphic intervals, the Williams Fork Formation, the Iles Formation, and the Rollins Sandstone Member (of the Mount Garfield Formation) or Trout Creek Sandstone Member (of the Iles). Each of these three stratigraphic intervals was then subdivided into two plays—a deeper gas play, which contains mainly sandstones that are gas bearing, and a shallower transition play that contains both gas-bearing and water-bearing sandstones. Variations in levels of thermal maturity were used to define the boundaries of the three deep gas plays and the three transition gas plays.

Two different methods were used to calculate resources. In the first method, the volume of sandstone in each of the six plays was calculated directly from sandstone isopach maps. Average depth of the play was estimated from overburden maps, and these depths were used to calculate the average pressure and average temperature for each play. An estimate of areal extent, average porosity, average gas saturation, and percent gas-saturated sandstone was then made for each play. This method produced a mean resource estimate for each of the six plays.

In the second method, values assuming different levels of probability were assigned to the geologic parameters such as play area and sandstone thickness. These probability ranges were then run through two complex probability programs. The first probability program assigns estimates to the gas potential of an individual play at the 95, 75, 50, 25, and 5 percent probability levels. The second program computes the same five probability levels to the aggregated sum of gas in all six plays using varying degrees of dependency between the plays. Using the aggregation program and the most likely degree of dependency of 75 percent between the plays, the mean in-place resource for the aggregated six plays is 419.55 tcf. There is a 95 percent chance of at least 274.45 tcf of in-place gas and a 5 percent chance of at least 605.33 tcf of in-place gas in the Mesaverde.

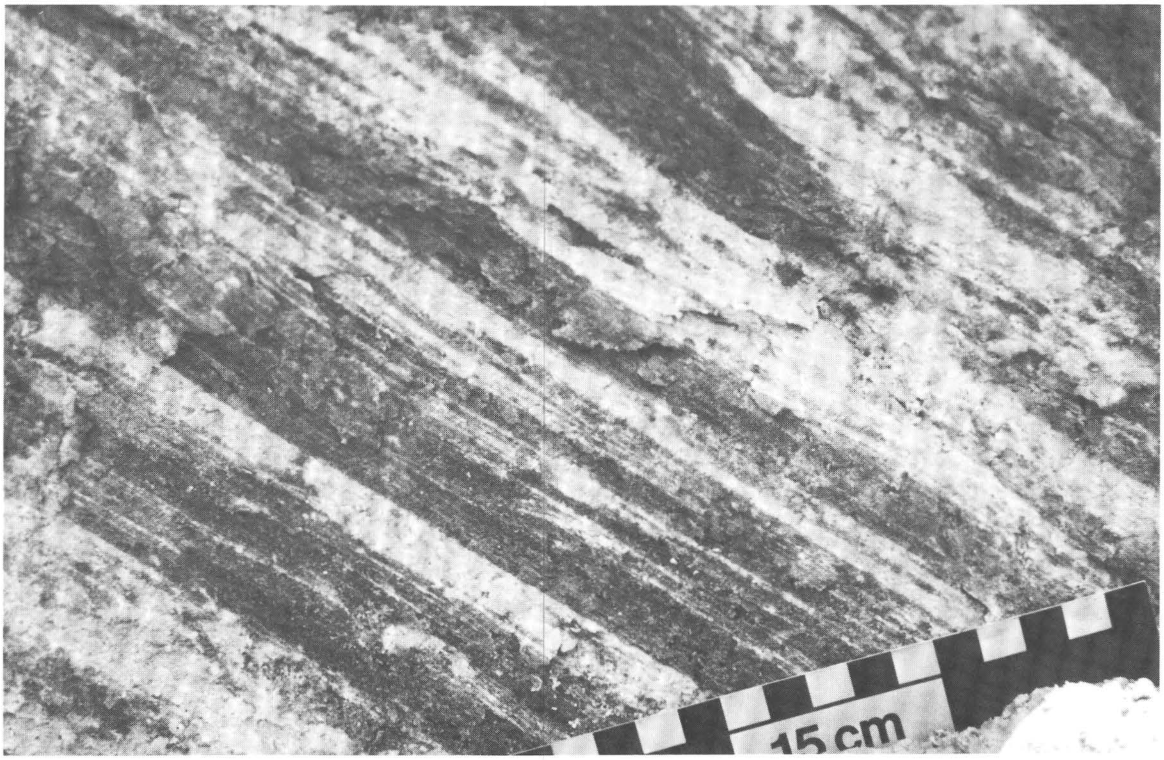
Six different recovery factors were estimated for each play: a low, most likely, and high recovery factor assuming current technology with a gas price of five dollars per thousand cubic feet (mcf); and a low, most likely, and high recovery factor assuming future advanced technology without a gas price specified. The recovery factors were applied to the probability ranges calculated using the two probability programs. Using the current-technology and five-dollar-gas assumptions, the range of estimates of recoverable gas for the aggregated six plays at the 95 percent, mean, and 5 percent probability levels are 2.92, 4.48, and 6.48 tcf for the low estimate; 8.75, 13.42, and 19.41 tcf for the most likely estimate; and 29.04, 44.45, and 64.20 for the high estimate. Using future advanced technology without a gas price specified, the range of estimates is 11.65, 17.85, and 25.80 tcf for the low estimate; 44.23, 67.95, and 98.39 tcf for the most likely estimate; and 128.04, 196.22, and 283.65 tcf for the high estimate.

Sedimentology of and Petroleum Occurrence in the Lower Permian Schoolhouse Tongue of the Weber Sandstone, Northwest Colorado

Samuel Y. Johnson, Christopher J. Schenk, Donald E. Anders, and Michele L. Tuttle

The Lower Permian Schoolhouse Tongue of the Weber Sandstone forms an extensive paleo-petroleum reservoir in northwest Colorado. The Schoolhouse Tongue is mainly bleached or oil-stained, gray to yellowish-gray sandstone of inferred eolian-sand-sheet origin. Low-angle (0°–15°) bedded very fine to fine-grained sandstone is the dominant facies. Beds are typically parallel or are truncated by low-angle deflationary surfaces, and deflation lags of coarse sand grains and granules are common. Crossbedded dune deposits (set thickness generally less than 50 cm) are a less common sand-sheet facies. Interbedded fluvial deposits are present in most sections. The sand-sheet deposits of the Schoolhouse Tongue are sedimentologically similar to those in the underlying red beds of the Middle Pennsylvanian to Lower Permian Maroon Formation, and the Schoolhouse Tongue is best construed as the uppermost sand sheet in the Maroon depositional sequence. The distinction between the Schoolhouse Tongue and the Maroon Formation is based on their different diagenetic histories.

The Schoolhouse Tongue has a maximum thickness of 66 m along Rifle Creek, the site of a late Paleozoic structural high. Oil staining in this area extends several hundred meters downward into the Maroon Formation and tens of meters upward into the unconformably overlying Permian and Triassic State Bridge Formation and the Triassic Chinle Formation. Away from Rifle Creek, the Schoolhouse Tongue thins to the north and pinches out (in 40 to 65 km) to the southeast and east into the Maroon Formation; and oil staining in strata bounding the Schoolhouse Tongue is negligible. The distribution of oil-stained rock suggests that



Oil-stained (gray) and bleached (white) sandstone of the Lower Permian Schoolhouse Tongue of the Weber Sandstone. Oil mainly occurs in secondary porosity resulting from migration of precursor organic acids and dissolution of carbonate cement. Photograph by S. Y. Johnson, from outcrops on east side of Rifle Creek, Garfield County, Colorado.

hydrocarbons were introduced at a point source, possibly related to faults on the margins of the paleo-high.

Oil in the Schoolhouse Tongue mainly occurs in secondary porosity resulting from migration of precursor organic acids and dissolution of carbonate cement. Sulfur isotopic data from the oil and from iron sulfides in ferruginous concretions are similar, suggesting that iron (present originally as grain coatings?) may have also been mobilized during this migration. Petroleum was trapped below overlying red siltstones of the State Bridge and Chinle Formations. Geochemical typing of the hydrocarbons in the Schoolhouse Tongue is consistent with a late Paleozoic source rock, perhaps the Lower to Middle Pennsylvanian Belden Formation.

Kinetic Models of Organic Reactions Applied to Burial History of Sedimentary Basins

J. David King

The purpose of this study is to apply principles of chemical reaction kinetics to the interpretation and reconstruction of burial-temperature histories within sedimentary basins. The technique produces finely tuned time and temperature syntheses that can be used as input to other models of oil and gas generation within the context of an overall basin analysis.

An excellent way to illustrate the thermal history of rocks penetrated by drilling is to construct a burial history with isotherms. These diagrams, which are graphs of depth versus geologic age, are constructed by plotting different strata at their present-day depth of burial, then projecting depth lines back to the time of deposition. The major unknown is paleotemperature. As a first approximation, the present-day heat flow (or geothermal gradient) can be extrapolated into the past. Burial history diagrams are frequently used to calculate TTI at different depths to determine the thermal maturity of possible petroleum source rocks.

Because the burial history effectively defines the time-temperature history of a rock at any depth, it is possible to *directly* calculate expected thermal maturity parameters versus depth based on kinetic modeling *without* correlating TTI values to the parameter of interest. Comparison of predicted and observed maturity values permits refinement of the postulated burial history to produce the best scenario. This comparison significantly constrains paleotemperature, rock ages, and unconformities.

The basic idea behind kinetic modeling is that chemical reactions proceed to equilibrium or completion predictably with respect to time and temperature. The relationship between time, temperature, and degree of reaction is defined by the rate equation for the reaction.

For any two chemical compounds R and P where it is known that R yields P with time and temperature, the rate equation for the reaction $R \rightarrow P$ can be used to calculate present-day amounts of R and P produced by a postulated burial-temperature history. Chemical analysis of down-hole rock samples for relative amounts of R and P provides observed data. If a systematic difference appears between calculated and observed quantities of R and P, the burial-temperature history can then be refined to produce the best match.

Distribution and Structure of Early Mesozoic Rift Basins on the Continental Margin of the Eastern United States

K.D. Klitgord and D.R. Hutchinson

Early Mesozoic rift basins are distributed across a 300-km-wide zone along the eastern seaboard of the United States. In addition to the exposed rift basins such as the Newark-Gettysburg basin, numerous rift basins have been mapped beneath the coastal plain and on the continental margin using seismic-reflection, magnetic, and drill-hole data. These rift basins are located within the shallow platforms and embayments (less than 5 km of postrift sedimentary cover) and along the hinge zone that separates these platforms and embayments from the marginal basins (such as Georges Bank basin), which contain 8–13 km of postrift sedimentary fill. The buried rift basins have been traced from the Bay of Fundy (Fundy rift basin) southward around the east side of the Gulf of Maine embayment, along the western edge of Georges Bank basin (Franklin rift basin), and then westward across the Long Island Platform (Atlantis, Nantucket, Long Island, and New York Bight rift basins). Rift basins rim the Salisbury Embayment and include a set of small basins on the west side (for example, the exposed Richmond Basin) and a set along the hinge zone (Delaware Bay and Norfolk rift basins). A rift basin (Brunswick rift) lies at the hinge zone between the Carolina platform and trough and is marked by the magnetic low of the Brunswick Magnetic Anomaly. This magnetic low swings westward and crosses onshore near Brunswick, Georgia; a rift basin has been imaged on seismic data by COCORP beneath this magnetic low.

Three types of structures appear to have controlled formation of rift basins buried on the United States continental margin. These structures are: (1) paired (antithetic) border faults that extend deep into the crust (such as the Long Island rift basin–Block Island fault pair), (2) discontinuity or ramp in a buried detachment surface near the position of the Appalachian gravity gradient (the Newark–New York Bight rift basin pair), and (3) low-angle detachment surface beneath the continental margin (Norfolk and Franklin rift basins). Many of these faults may represent reactivated Paleozoic structures.

Structural character of the rift basins is variable along and across the margin. Simple half-graben structures are located along the northeastern Georges Bank basin, southern Baltimore Canyon trough, and Carolina trough hinge zones. Crustal failure near the hinge zone in the northern Baltimore Canyon trough and southwestern Georges Bank basin created a more complex pattern of faulted blocks than the structures observed on the rest of the margin. Synrift deposits blanket a chaotic set of small prerift(?) crustal fragments. We interpret these fragments as debris left on a low-angle (east-dipping) detachment surface that separated the North American and African plates during the rifting phase.

Synrift sediment fill for many of the rift basins is characterized by tilted, subparallel reflectors landward of the basement hinge zone and a wedge-shaped reflector geometry seaward of the hinge zone. The change in reflector geometry across the hinge zone is a function of differential erosion in response to uplift landward and greater subsidence seaward of the hinge. A qualitative two-stage model of rift evolution explains these changes: an early stage is characterized by widespread half-graben formation along listric or planar normal faults, and a late stage is characterized by uplift and erosion at and landward of the hinge. Age control in the offshore region is poor, but biostratigraphic age data for synrift and early postrift sedimentary deposits and regional tectonic evolution models incorporating the European rift constraints indicate a Late Triassic age for early rift phase, Early Jurassic for the late rift phase, and late Early Jurassic for the end of rifting.

Organic Geochemical Studies of the Eastern U.S. Early Mesozoic Newark Basin—Phase Two

R.K. Kotra

Until recently, organic geochemical investigations of lacustrine sedimentary rocks from the Eastern U.S. early Mesozoic basins by the U.S. Geological Survey have been mostly restricted to outcrop material. During the first phase of our investigations, surface samples from the Hartford and Newark basins were shown to contain sufficient amounts of organic matter of appropriate type and maturity to produce fluid hydrocarbons. Pyrolysis, chromatography, mass spectrometry, nuclear magnetic resonance spectroscopy, elemental ratios, and stable isotope ratios were used to determine the amounts, types, and maturities of soluble organic matter (bitumen) and insoluble organic matter (kerogen). Estimates of the nature and amount of the more labile organic constituents from outcrop material are probably minimum values due to the effects of evaporation, oxidation, and weathering. Regional patterns of thermal maturation in these basins are currently being evaluated using the organic geochemical data from the surface samples.

The second phase of our investigations consists of examining continuous rock cores in the Passaic River basin in northern New Jersey. In this area exposure of sedimentary strata is poor; thus, the core sample set is the most complete stratigraphic section across the northern portion of the Newark basin. Well-preserved material to a depth of about 425 feet has been obtained. About 250 samples of red, gray, brown, and black mudstone and siltstone were used for organic geochemical studies. Other samples studied included a small number of sandstones of varying grain size, some with bitumen staining. The intervals represented are the Lower Jurassic Boonton, Towaco, and Feltville Formations and the Upper Triassic Passaic Formation.

The results of our first organic analyses of the core samples show that the total organic carbon content ranges from 0.05 percent to 4.1 percent; and many samples contain >2 percent. Hydrogen index (HI) values range from about 20 mg/g to more than 500 mg/g. Many of the gray-black and black mudstones have HI values of >300 mg/g. T_{max} values range from about 425 °C to >470 °C. Production index values are in the range from 0.1 to 0.4 for samples that did not appear to be obviously stained with bitumen. These initial results indicate that the organic matter spans the marginally mature to overmature stage. The HI and T_{max} values of individual samples indicate good oil and gas potential. Detailed characterization of kerogen and extracted hydrocarbons currently underway is designed to derive maturation parameters that are less dependent on the type of sedimentary organic matter present in these samples. This information will facilitate more accurate assessment of the abundance and thermal history of organic matter in the Newark basin.

The Role of Thermal History in the Preservation of Oil at the South End of the Moxa Arch, Utah and Wyoming—Implications for the Oil Potential in the Southern Green River Basin

B.E. Law and J.L. Clayton

The production of oil from the Lower Cretaceous Dakota Sandstone at the south end of the Moxa arch, immediately north of the Uinta Mountains in Utah and Wyoming, is unusual because the depth of occurrence is greater than 15,000 ft. At comparable depths elsewhere in the region, oil would be thermally destroyed. The preservation of oil in this area is largely due to an unusual thermal history.

The south end of the Moxa arch has a low thermal gradient (approximately 1.0 °F/100 ft) and unusually low levels of thermal maturity at depth (less than 0.6 percent vitrinite reflectance at 15,000 ft). A vitrinite reflectance (R_m) profile from this area shows that the thermal maturity gradient from 8,000 to 15,500 ft is very low (about 0.05 percent R_m/1,000 ft), indicating a nearly uniform distribution of heat. Lopatin-type thermal history reconstructions are not compatible with measured R_m data. The area is also characterized by the occurrence of relatively fresh water in the Dakota Sandstone, wherein total dissolved solids (TDS) range from 6,000 to 9,000 parts per million (ppm). North of this area, the TDS content of water in the Dakota exceeds 9,000 ppm. Some evidence suggests that these conditions also occur in the footwall of the Uinta thrust fault and in a narrow, 10- to 20-mile-wide area paralleling the Uinta thrust fault in the south end of the Green River basin.

On the basis of these observations and in the context of the geologic history, we suggest that convective and (or) advective heat transfer processes have played a prominent role in the thermal history of the south end of the Green River basin. The observed low level of thermal maturity in the Dakota requires a prolonged period of low temperature, comparable to the present thermal gradient. We conclude that the present thermal gradient came into existence in latest Cretaceous or Paleocene time, during or shortly after the faulting that occurred along the north flank of the Uinta Mountains. The faults and fractures, thus formed, provided pathways into the deep basin for the circulation of meteoric water. Under these conditions, convective and advective heat transfer processes effectively reduced the thermal gradient in the near vicinity of the Uinta Mountains thrust fault, precluding the development of high levels of thermal maturity. Thus, preservation of oil in the Dakota Sandstone at the south end of the Moxa arch has been facilitated by the occurrence of low temperatures that have been maintained through a geologically long time by convective and (or) advective heat transfer. By analogy, the potential for the occurrence of oil in the south end of the Green River basin is greatly increased because of the effective deepening of the "oil window."

Assessment of Gas Contained in Overpressured Low-Permeability Reservoirs in the Greater Green River Basin of Wyoming, Colorado, and Utah

B.E. Law, C.W. Spencer, R.A. Crovelli, R.F. Mast, G.L. Dolton, R.R. Charpentier, and C.J. Wandrey

Prepared in cooperation with the U.S. Department of Energy, Morgantown, W.Va.

The Greater Green River basin of Wyoming, Colorado, and Utah contains large amounts of gas in overpressured low-permeability Cretaceous and Tertiary reservoirs. The stratigraphic sequence in which these reservoirs occur reaches thicknesses of as much as 14,000 ft (4,267 m); it includes the Lower Cretaceous Dakota Sandstone and equivalents to the lower Tertiary Fort Union Formation.

The accumulation of thermogenic gas in these low-permeability source and reservoir rock sequences at rates greater than it is lost causes fluid (gas) pressure to rise above regional hydrostatic pressure. Thus, overpressuring is coincident with the occurrence of gas-bearing reservoirs. The gas-bearing overpressured sandstone reservoirs occupy the deeper parts of the basin, downdip from water-bearing normal-pressured reservoirs. Structural and stratigraphic trapping aspects in these unconventional reservoirs are not as important as in conventional reservoirs; the top of overpressuring cuts across structural and stratigraphic boundaries. The source of the gas is type III organic matter in the interbedded coal and carbonaceous lithologies, and type II and III organic matter in the interbedded marine shales.

The assessment of gas contained in these overpressured low-permeability reservoirs utilizes a reservoir equation in which the gas volumes are expressed as functions of the geologic and engineering variables. The variables include the areal extent of overpressured gas reservoirs, reservoir thickness, porosity, gas saturation, reservoir depth (temperature), geothermal gradient, pressure gradient, and gas compressibility.

The gas resource assessment approach is a probabilistic play analysis. The quantitative geologic model for a play consists of the reservoir equation with the geologic and engineering variables treated as random variables having probability distributions in the form of seven fractiles. The probabilistic methodology used to process the geologic data is an analytic method derived from probability theory as opposed to Monte Carlo simulation. On the basis of this methodology, two separate computer programs were designed—one for play analysis and another for play aggregation.

The Greater Green River basin gas-bearing interval was subdivided into five stratigraphic plays and the gas in-place resource for each play was estimated. The aggregate gas in-place resource of these plays ranges from 3,631 to 7,128 tcf, with 5,196 tcf as the mean estimate. Recoverable gas was estimated for each play under the following scenarios: (1) current technology, with a gas price of five dollars per thousand cubic feet and (2) advanced technology, with no dollar limit. For the *current* technology scenario, the aggregated recoverable gas ranges from 72 to 268 tcf, with 151 tcf as the mean estimate. For the *advanced* technology scenario, the aggregated recoverable gas ranges from 222 to 909 tcf, with 492 tcf as the mean estimate. For comparison, the National Petroleum Council in 1980 estimated the total in-place tight gas resource in the Greater Green River basin at 136 tcf and the maximum recoverable gas at 86.5 tcf. These estimates did not, however, include gas deeper than 15,000 ft (4,572 m).

Petroleum Geology of the People's Republic of China

K.Y. Lee and C.D. Masters

On the basis of geotectonics and geothermal gradients, petroleum-producing sedimentary basins in the People's Republic of China are grouped into eastern and western basins. The eastern basins reached full development in the late Mesozoic and Cenozoic as a result of extensional tectonics; they are the Songliao, North China, Ordos, Sichuan, Jianghan, Nanxiang, Subei, Eren, Sanshui, and Bose basins. The western group of basins, the Tarim, Junggar, Qaidam, Jiuquan, and Turpan basins, acquired their present configuration as a result of compressional tectonics during the early Cenozoic collision of the Indian subcontinent with the Eurasian plate.

Source rocks in both groups of basins consist of Mesozoic and Cenozoic, grayish-green and dark-gray to black, lacustrine mudstone and shale, except in the Junggar and Tarim basins, where Carboniferous and Permian marine black shale generated most of the crude oil. Higher than average geothermal gradients, which range from 30 °C to 70 °C per kilometer, are characteristic of the eastern basins. Reservoirs of the eastern basins are fluviodeltaic sandstone and Late Proterozoic and Paleozoic carbonate rocks containing solution-enhanced fractures and buried-hill traps. Reservoirs of the western basins comprise strata of all ages; however, fluvio-fan and delta deposits of Mesozoic age dominate. Multiple reservoir zones characterize oil fields in both groups of basins.

In 1986, the combined Songliao and North China basins produced about 70 percent of the 2.6 million barrels of crude oil per day produced in China. The remaining 30 percent was produced from the Junggar, Tarim, Qaidam, Jiuquan, Sichuan, Ordos, Nanxiang, Jianghan, and Bose basins. As of 1985, and cited from a 1987 study of Masters and others, Chinese crude oil identified reserves, both onshore and offshore, were assessed at 23.6 billion barrels, with there being a 90 percent probability that undiscovered recoverable resources lie within a range of 20–93 billion barrels of oil; natural gas reserves were estimated at 24.8 trillion cubic feet, with there being a 90 percent probability of the occurrence of undiscovered recoverable resources within the range of 122–467 trillion cubic feet of gas.

Processing Techniques for Deep Crustal Marine Multichannel Reflection Seismic Data—Examples from the Great Lakes

M.W. Lee, W.F. Agena, and D.R. Hutchinson

Multichannel seismic reflection data acquired over a hard, irregular water bottom are contaminated by strong multiple-interference and side-scatter noise that dominates the shot gathers and conventionally stacked data. These strong coherent noises combine not only to mask shallow subsurface reflections, but also to make it extremely difficult to analyze weak reflections from the lower crust and upper mantle. Thus, to perform a geologically sound interpretation and to properly migrate deep reflections, multichannel, pre-stack processing techniques based on the moveout differences between signal and noise are required.

In 1986, as a part of the Great Lakes International Multidisciplinary Program of Crust Evolution (GLIMPCE), more than 1,400 km of deep crustal reflection profiles were acquired in the Great Lakes region. The energy source was a 130 L (7,800 $in.^3$) tuned airgun array; 20 seconds of data were recorded at each shot point. Preliminary stacked sections were dominated by the coherent multiple and side-scatter noises. Post-stack dip filtering suppressed strong side-scatter noise of low apparent velocity, but it did not enhance the subsurface reflections as desired. Predictive deconvolution suppressed the short-period reverberations caused by source and receiver ghosts, but it could not adequately handle the long-period (on the order of 400 ms) multiples. Therefore, dip filtering in the shot domain was applied in order to suppress the side-scattering noise, and time-variant dip filtering in the CDP domain was performed in order to reduce the water-bottom multiple interference.

These pre-stack processing techniques were highly successful in reducing the coherent noise in the GLIMPCE seismic data. A post-stack, signal-enhancement technique based on the strength of the reflected energy provided additional enhancement in the deep reflectors. Examples of banded Moho reflections around 12–14 seconds and of the Keweenawan rift basin within Lake Superior demonstrate the effectiveness of these seismic data processing techniques.

Implications of Trace-Element Concentrations in Modern Tree Fern Tissues for the Origin of Elements in Vitrinites of the Pittsburgh Coal Bed

Paul C. Lyons and Curtis A. Palmer

Tissues from the modern tree fern *Alsophila tricolor* and vitrinite concentrates from the Pittsburgh coal bed (which is known to be vitrinite rich and derived from mainly tree fern species) were analyzed for 21 elements (fig. 1) by instrumental neutron activation analysis. The following maceral precursors are suggested for the tissues analyzed: telinite (xylem), collinite (parenchyma), and telinite (sclerenchyma). As compared to the Pittsburgh coal vitrinites (fig. 1), contents of the alkali metals (Na, K, Cs) and alkaline earths (Ca, Ba) are higher in all fern tissues analyzed; the reverse is true for Al. As compared to trunk sclerenchyma, the root sclerenchyma has similar or greater concentrations of all elements and the root parenchyma has concentrated most elements when compared to both trunk and root sclerenchyma; the xylem has the highest concentrations of Sc, Mn, Sm, and Zn but the lowest concentrations of Al when compared to other tissues (fig. 1). Cl is similar in concentration in all tissues analyzed.

The results indicate a primary concentration of almost all elements by histological fractionation in the tree fern and the reprecipitation of Al and its fixation in clays or other aluminum forms in the vitrinite. Because the parenchyma is the most degradable of all the tissues in the tree fern, it is a good potential source of metals mobilized during degradation and fixed in other forms. However, the relatively high concentrations of alkali metals and alkaline earths in all tissues, as compared to those in the Pittsburgh coal vitrinites, indicate probable substantial loss of these elements from the peat-coal system by dewatering and other processes. The xylem is a good potential source of Zn and rare earths in the Pittsburgh coal.

Basin Analysis Studies of Cambrian through Mississippian Rocks, Powder River Basin, Wyoming and Montana

David L. Macke

The Cambrian through Mississippian sedimentary rocks of the Powder River Basin represent nearly half of Phanerozoic time, yet they remain virtually unexplored for petroleum in the subsurface. The lack of an economic reason to study these rocks has hampered the development of precise depositional models for these sequences, as have the depth of prospective beds and some longstanding misconceptions about the regional stratigraphy.

Rocks of the same age range in the Bighorn and Williston Basins and in the Central Montana trough have produced much oil and gas, as have the overlying Pennsylvanian strata of the Powder River Basin. A synthesis of published stratigraphic information, together with a regional analysis of sedimentary sequences, has been undertaken to evaluate the economic potential of the pre-Pennsylvanian Paleozoic formations in the Powder River Basin.

Stratigraphic studies have documented a succession of marine transgressions and regressions on the flanks of a land area in southeastern Wyoming. Through most of early Paleozoic time, the land area persisted as a subdued geographic feature; at the end of the Mississippian, it rose. Erosion during episodes of marine regression, especially during Late Silurian and Devonian, has removed much of the depositional record in the area; but onlap can be demonstrated with relative certainty for Ordovician and Devonian into Mississippian age.

The repetition of sedimentological features in the rock record indicates persistent geologic controls in the region, and suggests that the paleoenvironments might have provided targets for exploration.

The Petroleum System—A Classification Scheme for Research and Resource Assessment

Leslie B. Magoon

A petroleum system includes those elements that are essential for an oil and gas deposit to exist in nature.

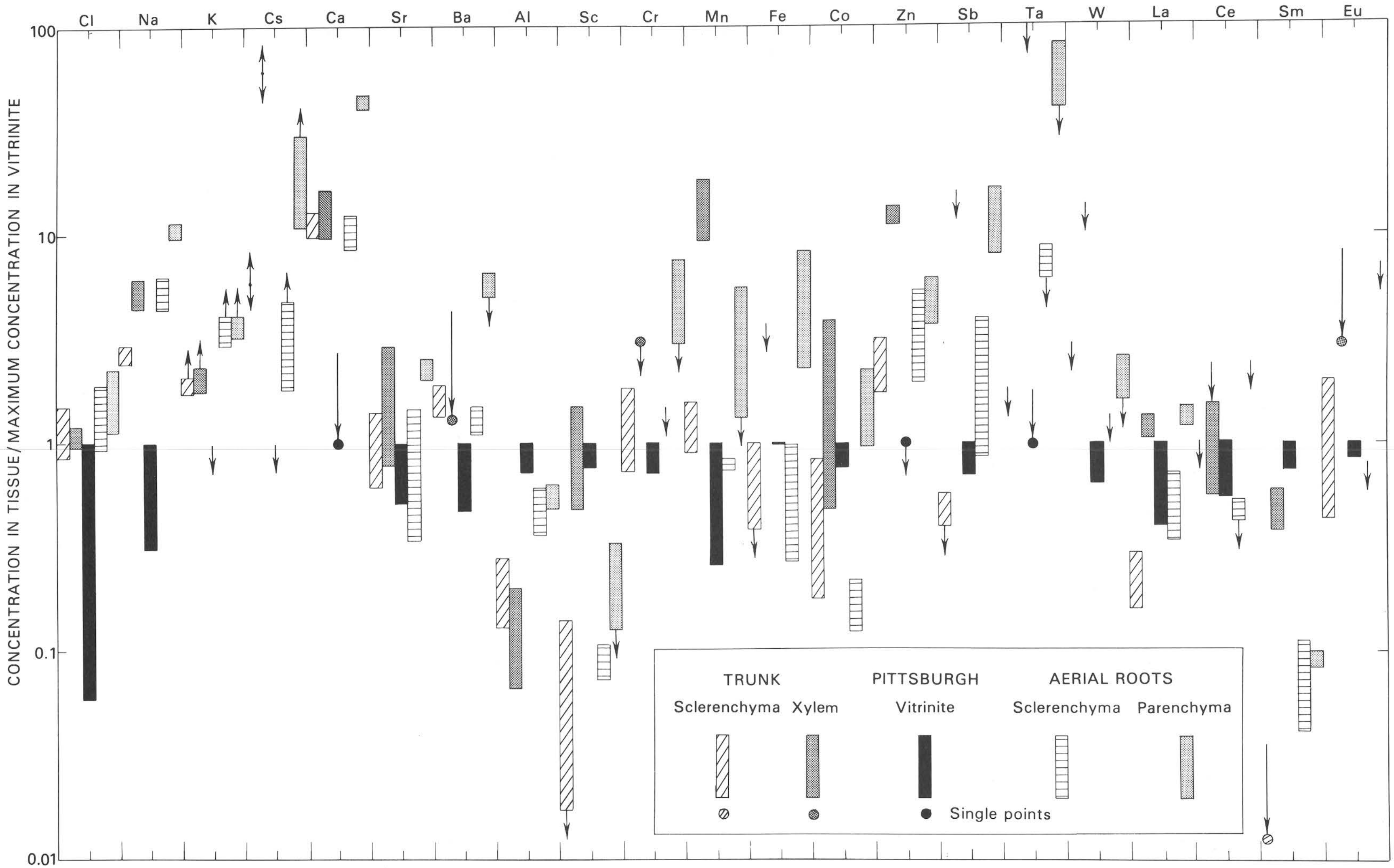


Figure 1. Comparison of trace-element concentrations in vitrinites of the Pittsburgh coal bed with those of tissues in the modern tree fern *Alsophila tricolor*. Values are normalized to the maximum concentrations in the vitrinites of the Pittsburgh coal bed. Tail of arrows indicates maximum or minimum values of upper or lower limits, respectively, of the ratio of elemental concentration in tissue over maximum elemental concentration in Pittsburgh vitrinites. Patterned dots with arrows indicate single ratios only, rather than two or three ratios as represented by columns.

The basic elements include a petroleum source rock, migration path, reservoir rock, seal, and trap. All these elements must be correctly placed in time and space for a petroleum deposit to occur. The stratigraphic, areal, and temporal extent of the petroleum system is specific. Stratigraphically, the system is limited to the following rock units: petroleum source rock, rocks through which migration occurred, reservoir rock (trap) and rock overburden required for maturity. The areal extent of the petroleum system is defined by a line that circumscribes the mature source rock and all oil and gas deposits (conventional and unconventional) that emanated from that source. The temporal extent of the system is that span of geologic time beginning with deposition of the source rock to the time of latest petroleum migration.

A petroleum system can be identified in terms of geochemical correlation of oils and source rocks at three levels of certainty: known(!), hypothetical(.), or speculative(?). A known identification includes those petroleum systems where successful oil-source rock correlations are obtained. A hypothetical identification includes those petroleum systems where oil or gas deposits can be shown to be genetically related, and source rocks can be geochemically documented, but no geochemical correlation exists. A speculative identification includes those petroleum systems where only geologic evidence supports a relationship between the petroleum deposit and its source rock. I propose that the petroleum system designation include the name of the source rock, followed by the name of the major reservoir rock and a symbol expressing the level of certainty, for example, the Beluga-Sterling(.).

After a petroleum system is identified, named, and its level of certainty established, it must be classified. The classification scheme is based on the reservoir rock type (siliciclastic or carbonate), source rock kerogen type (I, II, or III), and as either a purebred or a hybrid system. This scheme allows for 12 separate categories of petroleum systems. A purebred petroleum system is one whose elements were formed in a single sedimentary basin during a single tectonic cycle, whereas a hybrid petroleum system is one whose elements formed in at least two superimposed sedimentary basins and tectonic cycles. In Alaska's Cook Inlet basin, for example, the Beluga-Sterling(.) petroleum system, a series of biogenic gas deposits, is a purebred system, because the source and reservoir rocks were deposited in a single sedimentary cycle; the Tuxedni-Hemlock(.) petroleum system is a hybrid system, because the Jurassic source rock was deposited in a forearc marine basin and separated by a regional angular unconformity from the Tertiary reservoir rock and overburden, which were deposited in a nonmarine basin.

USGS geologists have classified the petroleum systems in the United States. As we classify the Nation's petroleum systems using these criteria, we may clearly identify the various elements of each system, and then compare across systems to generalize the mechanism and capacity to generate, migrate, and trap hydrocarbons. Plans call for selected petroleum systems to be researched and assessed; among the first studied will be a petroleum system on the North Slope of Alaska.

Estimates of Undiscovered Recoverable Oil and Gas Resources for the Onshore and State Offshore Areas of the United States

R.F. Mast, G.L. Dolton, R.A. Crovelli, R.B. Powers, R.R. Charpentier, D.H. Root, and E.D. Attanasi

How much oil and gas remains to be discovered in the United States is an important question as well as a subject of controversy. The U.S. Geological Survey has published estimates over the years; this report presents a new assessment. Estimates of undiscovered recoverable conventional oil and gas resources were made for more than 240 geologically defined plays in 80 petroleum provinces covering the onshore and the State offshore areas of the conterminous 48 States and Alaska. The methodology developed was flexible and handled the variety of play situations encountered. The results can be described not only in terms of total volumes of oil and gas but also in terms of geologic setting, accumulation size, and number of accumulations.

The plays were developed by geologists for each petroleum province. Geologic, geochemical, and geophysical data were used to define and bound each play and to provide a basis for assessment. Resource estimates for undiscovered accumulations with recoveries larger than 1 million barrels of oil or 6 billion cubic feet of gas were made using a play analysis method that required estimation of play and accumulation favorability or risk, the size distribution of undiscovered recoverable accumulations, and the distribution of the number of undiscovered accumulations. Size data from either discovered accumulations in each play or from an analog play were employed to estimate the size of undiscovered accumulations. Curves were fit to the size data for the discovered accumulations which were generally split into three sequential parts: the first, second, and last 1/3 of the accumulations discovered in each play. Parameters from these fitted curves provided a basis for estimating the size distributions for the undiscovered resources. The numbers of undiscovered accumulations greater than the minimum sizes were estimated, utilizing play maps showing well penetrations and the areal sizes of the oil and gas accumulations, along with the drilling history. Finally, ratios of associated-dissolved gas-to-oil and condensate-to-gas were estimated. All these approximations were used to calculate the probabilistic estimates of conventional recoverable oil, gas, and natural gas liquids in accumulations greater than the cut-off values. The play analysis methodology used to compute these estimates is an analytical method derived from probability theory as opposed to Monte Carlo simulation.

Undiscovered recoverable resources in fields smaller than the cut-offs of 1 million barrels and 6 billion cubic feet were estimated for each province. Statistical extrapolation from the numbers of fields in field-size classes greater than the cut-offs produced estimates of the numbers of fields in field-size classes below the cut-offs. The number of small fields already discovered and the volume of oil and gas in these fields were also utilized to estimate the undiscovered resources in small fields.

Economically recoverable resources were determined by applying minimum economic sizes to play estimates and estimating the percentage of the small-field resources thought to be economic. In general these percentage estimates were based on the nature of the plays in the province and the estimated depth of these undiscovered resources.

Province level results were formed by aggregating the play estimates and the small-field estimates for both undiscovered recoverable and economically recoverable undiscovered resources. Regional and National level results were developed by aggregating province and region results respectively.

The results of the assessment are tabulated below. The resource estimates are smaller than those published by the U.S. Geological Survey in 1981. However, the data used were somewhat different because the method employed was different. Some of the resources classified as undiscovered in 1981 are now classified as identified, unconventional or inferred resources; and the resources discovered from 1981 to 1986, especially in some onshore frontier areas, were disappointing in view of the very large exploration drilling effort expended.

Undiscovered conventional resources
[TCF, trillion cubic feet]

	Crude oil Billions of barrels			Non-associated gas TCF			Associated-dissolved gas TCF		
	F95	F5	Mean	F95	F5	Mean	F95	F5	Mean
				Recoverable resources					
Total	19.6	51.9	33.4	141.0	295.0	209.2	31.0	61.9	44.8
Lower 48	15.8	25.2	20.2	124.5	204.4	161.3	26.4	44.6	34.8
Alaska	3.6	31.3	13.2	10.8	122.8	47.9	2.6	24.5	10.0
				Economically recoverable resources					
Total	14.0	42.0	25.7	118.5	199.3	155.6	24.7	42.9	33.0
Lower 48	14.4	23.7	18.7	117.6	198.2	154.6	24.5	42.7	32.9
Alaska	0.9	21.0	6.9	0.1	3.2	1.0	0.0	0.4	0.2

U.S. Energy Supply from the Perspective of World Petroleum Geology

Charles D. Masters

The purposes of the World Energy Resources Program assessment are to quantify the regional distribution and potential for the occurrence of petroleum resources worldwide, and to establish a base-line of world petroleum geology knowledge that will permit the early recognition of anomalous exploration results that might affect assessment. When the program began, the available data base was the geologic literature of the world and a country-level understanding of cumulative production and reserves. Given the required time frame of response and our personnel resources, assessment methods had to parallel those of the domestic petroleum assessments conducted by the USGS and published in 1975 and 1981—that is, a modified delphi procedure. The principal means to develop scaling factors for the subjective assessment included regional finding-rate projections, volumetric calculations from basin analog determinations, and locally discrete play analysis reservoir calculations. With developing program maturity, the geologic and reserves data bases have expanded to play-level understanding in many basins, and field reserves data can now account for the occurrence of more than 90 percent of world reserves. This expanded data set offers the possibility of selected field-size distribution assessment analysis and certainly more sophisticated finding-rate studies by field-size class. In addition, we are continuing to develop regional understanding of remote areas such as the Arctic and the Antarctic, as well as the occurrence of petroleum as it relates to paleotectonic plate positions and to principal zones of source rock occurrence. We are also investigating the occurrence of condensate, to improve our ability to assess its resource potential.

Results of our program studies indicate that petroleum occurs in such large quantities as to yield a barrels-of-oil-equivalent (BOE) reserve-to-production ratio of 50. Though the quantity is large, the distribution of discovered conventional petroleum is narrow, and our assessment identifies no new areas that might significantly alter that distribution. On the other hand, a very large recoverable unconventional resource of extra heavy oil and bitumen, of comparable dimension to the Middle East conventional oil, exists in Venezuela and Canada. This resource could provide a Western Hemisphere counterbalance to Middle East resource dominance. Though conventional resources are narrowly distributed, present-day oil production is not, with only 31 percent deriving from OPEC, 38 percent from the United States and the U.S.S.R., and the remaining 31 percent from more than 60 individual countries. A key to near-term energy security lies in maintaining diversified sources of conventional petroleum supply until such time as the unconventional oils can find their place in the market, along with a greatly expanded use of coal.

Seismic Stratigraphy of the Békés Basin, Southeastern Hungary

Robert E. Mattick, János Rumpler, Antal Ujfalusy, Béla Szanyi, and Irén Nagy

The Békés basin, a subbasin of the Pannonian Basin, is located in southeastern Hungary, covers an area of about 3,000 square kilometers, and contains Neogene and younger lacustrine sedimentary rocks that locally are in excess of 7,000 meters thick. Successful hydrocarbon exploration in the Békés basin and surrounding areas began in the early 1960's, and as a result of extensive exploration since that time, all of the major structures and most of the minor structures have been located and drilled. In an effort to begin a systematic search for subtle traps, the USGS and the Hungarian Oil and Gas Trust jointly completed a basin analysis study of the Békés basin. The results of seismic stratigraphic study are summarized herein.

The Neogene history of the Békés basin reflects one of the last episodes of infill of the much larger Pannonian Basin. It was not until other subbasins to the northwest, north, and northeast became filled by southward progradation of massive sediment wedges that the major river systems which transported sediments were able to advance to the area of the Békés basin. Thereafter, rapid deltaic infilling of the Békés basin proceeded as major river systems converged and lacustrine sedimentation became confined to an increasingly small basin.

Post-rift infilling of the Békés basin reflects gradually shallowing water conditions. This shallowing resulted from sedimentation rates that were higher than basin subsidence rates. Initial water depths in the basin were about 1,500 m, but the last sequences of well-developed deltaic wedges were deposited in water depths of 200–400 m.

On seismic records, three sedimentary rock units can be mapped. From oldest to youngest they are: (1) a basal marl and turbidite sequence; (2) a prograding sequence that represents an episode of delta construction; and (3) an uppermost unit which represents delta plain facies in which depositional environments varied from shallow lake, fluvial, and marsh to terrestrial soils.

The basal turbidite sequence in the southern part of the basin is inferred to consist of distal turbidites. To the north, however, this unit consists of more proximal turbidites.

During much of the early history of the Békés basin, large volumes of clastics, transported by rivers, were channeled along structural depressions; these troughs were derived from pre-rift or early rift topography of the basin. Along the northern margins, sediments were transported basinward through subaqueous structural depressions, and in some of these areas, large subaqueous fans—a few possibly containing coarse-grained sandstones—are well developed near the base of the slope.

In later stages of basin infill, sand was derived primarily from the upper part of the prograding delta slope and moved downslope by slumping, sliding, mass flow, and turbidity currents. In this later stage, subaqueous fan systems and channels on the slope were poorly developed.

Rates of deposition are calculated to be 200–310 m/million years for the basal turbidite sequence, 1,000 m/million years for the prograding sequence, and 500 m/million years for the uppermost sequence.

A strong unconformity mapped on seismic records in the southeastern part of the Békés basin is interpreted as representing massive, subaqueous scour that occurred during the Neogene as waters of the Pannonian lake flowed eastward out of the basin.

Effects of Climate, Tectonism, and Variations in Sea Level on the Formation of the Cretaceous Coals of North America

Peter J. McCabe, Michael E. Brownfield, Dan E. Hansen, Robert D. Hettinger, Mark A. Kirschbaum, and J. David Sanchez

Extensive deposits of Cretaceous coal-bearing strata are present in western North America, extending from the North Slope of Alaska to northern Mexico. Most of the Cretaceous sediments were derived from the active Cordillera region and were deposited in foreland basins on the western margin of the Western Interior seaway. A multidisciplinary study is in progress to document, and attempt to explain, the temporal and spatial distribution of the Cretaceous coals. The study examines the effects of variations of paleoclimate, tectonics, and relative sea level on a continent-wide scale. In addition, coal quality is related to the regional depositional settings.

Many aspects of coal quality (for example, maceral composition, ash content, sulfur content) are determined by the flora and the hydrology of the mire in which the original peat accumulated. The existence of Cretaceous coals throughout the length of the Western Cordillera provides a unique opportunity to determine variations in mire type with climate over a range of 50° of paleolatitude, and to examine the effects of these variations on coal quality. The relationships between coal beds and associated clastic facies should also be expected to change with varying mire types.

Recent developments in our understanding of foreland basin evolution, Cretaceous sea-level changes, and peat-forming environments make this an optimal time to commence a regional synthesis of North America's Cretaceous coals. Results of this study should aid the development of better predictive models of coal quality and seam thickness. These models will take into account the effects of major controls on sedimentation (climate, tectonics, sea-level changes) rather than just the local depositional environment. Many of the major coal deposits of the world lie within foreland basins, and it is hoped that the models derived from this study will be transferable to coal deposits of differing age in other areas.

Offshore Resource Geology of Central California

David S. McCulloch and Stephen D. Lewis

The hydrocarbon resource potential of offshore central California ultimately resides in shelf and slope basins, and possibly in adjacent large deep-sea fans. However, with present water-depth limited technology, thin near-shore late Tertiary shelf basins are the principal exploration targets. Although they rest on a variety of yet ill-defined accreted basement blocks, these shelf basins have generally similar late Neogene structural and stratigraphic histories. These histories suggest that the continental margin was emergent and that erosion generally extended to Cretaceous basement during the global Oligocene low sea level. At about the Oligocene-Miocene boundary (23 Ma), a possible change in Pacific-North American plate motion may have accounted for the start of transtension that was manifested along the margin by subsidence and marine volcanism, and in some basins, by the initiation of transtensional basement structures. Structural growth continued in the Miocene as expressed by relative subsidence of the basins and elevation of partially fault controlled elongate structural highs along the outer edge of the shelf. Subsidence was accompanied by deposition of silica-rich hemipelagic strata (Monterey Formation equivalent) at bathyal and mid-bathyal depths.

Transtension was replaced by transpression at about the time (≈3–5 Ma) of a change in relative Pacific-North American plate motion, and terrestrially derived sediment that flooded into the shelf basins probably reflects coastal uplift. Transpression was accompanied by the growth of generally coast-parallel folds and compressional faults. In some basins earlier transtensional basement structures localized the younger folds and compressional faults. Large vertical-separation faults along basin boundaries were structurally overprinted by compression, giving them the appearance of high-angle reverse and thrust faults. Shallow Holocene basins that developed on the shelf, folded and faulted sea-floor strata, and compressional and right-slip earthquake focal mechanisms indicate continuing transpression on the shelf.

Monterey rocks (chert, porcellanite, siliceous shale) originally deposited as biogenous silica, fine terrigenous debris, and organic matter are the primary exploration targets. These rocks were commonly encountered along most of the offshore margin in a 1960's round of exploratory drilling, but because of a poor onshore production history, they were untested despite encouraging hydrocarbon shows. Recent experience onshore and offshore has shown comparable strata to be producible, primarily from fracture reservoirs; and recently developed fields in the southernmost basin (including a giant and several smaller fields in offshore Santa Maria basin) have developed production from these strata. The combination of late Neogene structures, formation brittleness enhanced by diagenetic silica alteration, and hydrocarbon generation at moderate temperatures and shallow burial depths makes these strata attractive exploration targets.

Interpretation of Seafloor Processes in the Gulf of Mexico Using the GLORIA Sidescan Sonar System

Bonnie A. McGregor and David C. Twichell

GLORIA sidescan-sonar images provide a unique view of the seafloor in the deep water of the Gulf of Mexico. A better understanding of the morphology, surficial geology, and sedimentary processes of the continental slope and rise in the Gulf of Mexico is important for evaluating and developing energy and mineral resources, and for siting seafloor structures. The GLORIA data provide information on depositional environments and geologic processes that is important in developing depositional models useful as analogs in understanding the rock record.

The EEZ in the Gulf of Mexico can be divided into three major provinces: a salt deformation province in the western section, the Mississippi Canyon and Fan system in the central section, and a carbonate province in the eastern section, which is separated from the terrigenous Mississippi Fan by the Florida Escarpment.

In the western gulf, the most striking feature on the imagery is the Sigsbee Escarpment, which marks the seaward edge of the salt deformation province. Vertical relief on the escarpment is approximately 500 m, and piles of debris along the base are visible on the sonographs, suggesting that sediment is eroded from the escarpment. Seaward of the escarpment, patches of seafloor with numerous lineations are interpreted as bedform fields formed by the reworking of debris from the escarpment. Landward of the escarpment, the continental slope has a very complex morphology, formed in response to intrusion by the salt.

The Mississippi Canyon and Fan system is the dominant feature in the central gulf. The Mississippi Canyon on the slope and upper fan contains debris-flow deposits, and the flows have spilled over the canyon walls at meanders. As the filled Mississippi Canyon is traced seaward onto the middle part of the Mississippi Fan, a meandering channel becomes apparent. Adjacent to this channel on the eastern fan, the seafloor is marked by very intricate flow patterns. This region is interpreted to contain debris-flow deposits emanating from the Mississippi Canyon and covering most of the fan.

In the northeastern gulf, a submarine debris-flow deposit is present near the mouth of DeSoto Canyon. A meandering channel partially buried by the deposits emerges and trends southward, parallel to the Florida Escarpment. Another channel (perhaps abandoned) lies closer to the base of the escarpment, and a tongue of the debris-flow deposits from DeSoto Canyon fills the channel.

The dominant feature in the eastern gulf is the Florida Escarpment, which has a gradient of as much as 40° and relief ranging from 1,000 m in the north near DeSoto Canyon to 2,500 m west of the Florida Keys. Numerous scarps having up to 250 m of relief are present in the Tertiary carbonate sediments above and landward of the escarpment. These scarps are the product of mass wasting, and some align with canyons that dissect the escarpment. The canyons appear to be conduits for massive slumps of the Tertiary sequence, resulting in the deposition of carbonate material in the deep water of the gulf, interbedded with clastic material of the Mississippi Fan.

The GLORIA mosaic demonstrates that mass wasting is much more extensive in the Gulf of Mexico than previously thought, that it exhibits a variety of styles and volumes, and that it has been a major process in the distribution of sediments in the deep water of the Gulf of Mexico. Four submarine channels can also be identified meandering across the floor of the gulf, providing pathways for the transportation and distribution of sediments in deep water.

The Distribution of Rare-Earth Elements in the Pittsburgh Coal Bed

James S. Mee, Curtis A. Palmer, and Charles L. Oman

It has been generally believed that the rare-earth element (REE) distribution in coals is similar to that of shale. To examine this hypothesis further, 114 coal samples (<30 percent ash) from the Pittsburgh coal bed in Pennsylvania, West Virginia, and Ohio were analyzed by INAA for the REE (La, Ce, Sm, Eu, Tb, Yb, and Lu). These samples were normalized to the North American Composite Shale, NACS, as explained in a 1968 study by L.A. Haskins and others, to better illustrate the differences in the REE concentration between the coals studied and to provide a better understanding of the conditions of formation and the migration of REE through the coal bed.

The slope of the REE pattern may be used to determine the relationship between the REE pattern of NACS and sample coals. The comparison of the ratio of the light REE (LREE–La, Ce, Sm) and the heavy REE (HREE–Tb, Yb, Lu) can be estimated as a La:Lu ratio.

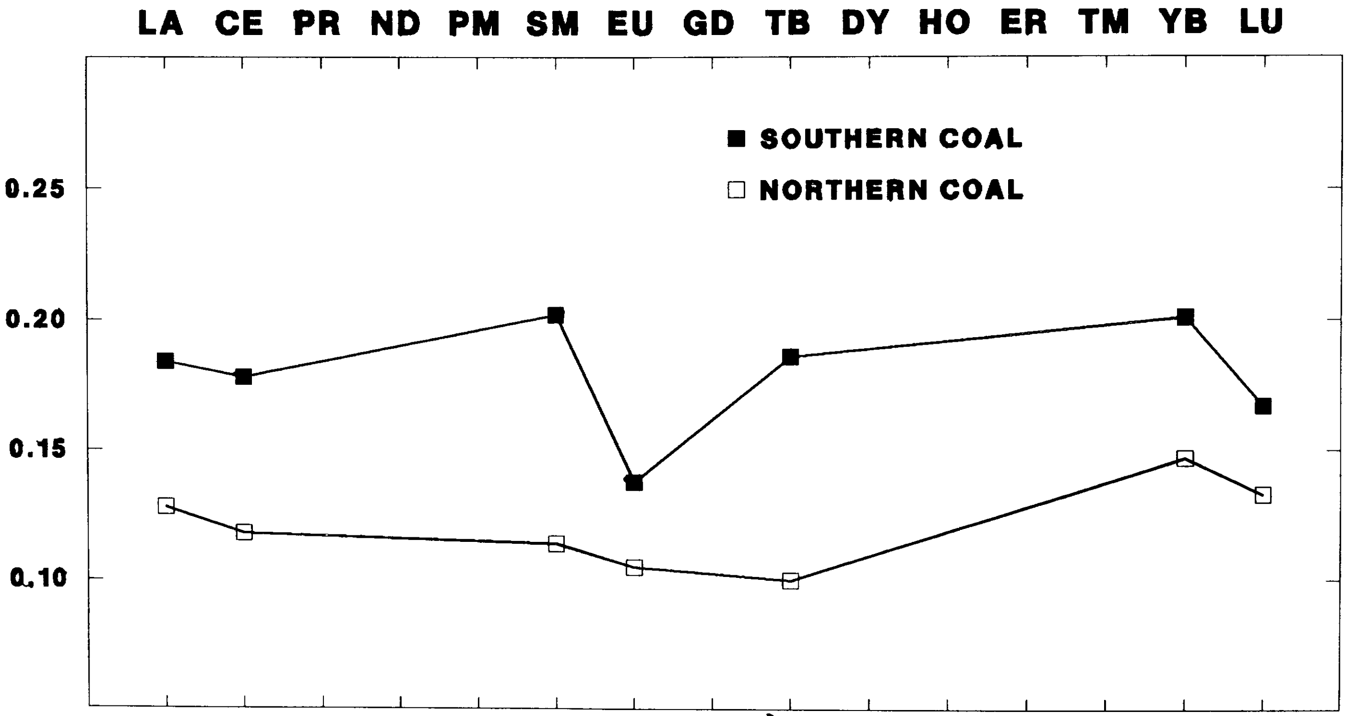


Figure 1. The northern coal is representative of a "flat" rare-earth pattern, taken from the northern field of the Pittsburgh coal bed. The southern coal is representative of the majority of the coals in the Pittsburgh coal bed, which have a Eu anomaly.

The samples studied have an average La:Lu of approximately 1, confirming the similarity of the REE pattern to that of shale.

The Eu abundances of the coal samples, however, show a distinct difference in the samples depending upon the locality in the coal beds. The extent of the difference (Eu anomaly) may be measured by Eu:Eu*, where Eu is the actual normalized concentration of europium and Eu* is the "expected" value by interpolation between Sm and Tb. Only the coals from the northern part of the coal bed, north of lat 40° N., which represent less than 15 percent of the coal bed, have REE patterns that are similar to the NACS, Eu:Eu*≈ 1, which demonstrates similarities to the REE patterns of the NACS. A majority of the coals south of lat 40° N. have Eu:Eu* ratios that range from 0.8 to 0.5 (fig. 1).

The differences between the northern and southern coals may be due to several environmental conditions. The climatic differences in the swamp and a slower burial rate may have prevented Eu^{+2} from forming in the northern section. The Eu anomalies, present in the REE patterns of the southern coals, are probably a result of Eu^{+3} being reduced to Eu^{+2} due to the conditions present during early diagenesis, for example, rapid burial and differences in eH and pH.

Seismic Reflection Profiles Across the Eastern Bighorn Mountains Between Buffalo and Story, Wyoming

John J. Miller, Myung W. Lee, John A. Grow, E.N. Hinrichs, and S. L. Robbins

Two multichannel seismic reflection lines west of Story and Buffalo, Wyoming, were obtained (courtesy of Chevron U.S.A., Inc.) and reprocessed by the USGS. The data were recorded using portable equipment having a dynamite energy source, 120 channels per shot, 6-second record length, 2-ms sample interval, and geometry affording 15-fold subsurface coverage.

Reprocessing was accomplished using the USGS-owned DISCO seismic data-processing system software. The data were processed to the stage of unmigrated stack using a standard processing sequence that included pre-stack deconvolution and two iterations of residual statics calculations. Datum and residual static calculations were problematic because the near-surface velocity varied abruptly due to an outcrop of overthrust granite. Special attention was therefore given to these processing steps. Wave equation migration applied after stacking used a velocity model determined from a series of constant-velocity migration tests. The velocity model developed to convert the data to depth integrated velocities determined from closely spaced stacking velocity analyses with acoustic logs from nearby boreholes.

After reprocessing, these two lines clearly show subthrust sedimentary rocks of Paleozoic through Paleocene age overthrust by Precambrian granites and gneisses. A reflection from the thrust fault plane dipping 30° W. is imaged. The Buffalo Deep fault, a high-angle reverse fault in the sedimentary rock sequence, appears at the eastern end of both lines.

Stratigraphic Framework of the Pannonian Sequence (Neogene), Békés Basin, Southeast Hungary

C.M. Molenaar, I. Révész,[1] I. Bérczi,[1] A. Kovács,[1] Gy. K. Juhasz,[1] I. Gajdos, and B. Szanyi[1]

The Békés basin, a sub-basin of the Pannonian basin in southeastern Hungary, is a late Tertiary structural basin that was filled by as much as 6,500 m of Neogene sandstone, siltstone, claystone, and marl. These rocks, known as the Pannonian sequence or group, are oil and gas productive in structural traps around the flanks of the basin. Because of rapid depositional rates and the lacustrine depositional environment, biostratigraphic zones within the thick sequence are lacking. The large amount of good multichannel CDP seismic data, however, provides a good method of establishing time correlations between wells and provides information on depositional environments. In general, the seismic facies patterns correspond to the depositional environments, which in turn reflects established formational or lithogenetic terminologies.

Well-log cross sections correlated with seismic data indicate that the Pannonian sequence was deposited in a wide range of depositional environments, ranging from deep basinal lacustrine to basin slope to shallow lake and delta plain to alluvial plain. Essentially one depositional cycle is represented and the facies are highly diachronous. The basinal facies consist of a basal distal clay marl unit overlain by turbidites containing thick amalgamated sandstone beds. The slope facies consist of clay marls or shales, turbidites, and slump deposits that grade upward into predominantly clay marls. The shallow-lake, delta-plain, and alluvial-plain facies consist of interbedded sandstone and clay marl and (or) lignitic shale.

The relief of the slope or clinoform beds indicates that basinal beds were deposited in water depths greater than 500 m. Depositional dips of the slope facies beneath a conspicuous shelf break were at least 3°–5°.

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[1]Hungarian Oil and Gas Trust, Budapest, Hungary.

Peat Deposits on Coastal Sumatra— A Modern Analog of Coal Formation

Sandra G. Neuzil, C. Blaine Cecil, Supardi[1], A.D. Soebakty[1], Cortland F. Eble, Christopher Wnuk, and Lim Meng Sze Wu[2]

Detailed study of modern peat deposits may be used to develop predictive models for the occurrence and quality of coal. Modern peat deposits on coastal Sumatra appear to be an excellent analog for low-ash and low-sulfur coal beds that are inferred to be derived from peat that formed in a tropical environment. These modern tropical peat deposits are areally extensive, thick, domed, rainfall dominated (ombrogenous), low in ash (<10 percent) and sulfur (<1 percent) contents, and acidic (pH 3–6).

Field studies were conducted in the Siak Kanan and Bengkalis peat deposits in Riau Province, Sumatra. The Siak Kanan peat deposit is the northern part of a large peat swamp that is bounded on the northwest by the Siak River, on the northeast by Panjang Strait, and on the south by the Kampar River. It is on the coastal plain and contains 1,100 km^2 of peat >1 m thick (13.5 m maximum thickness). The Bengkalis peat deposit covers most of Bengkalis Island, located 10 km off the coast of Sumatra, and contains 700 km^2 of peat >1 m thick (10 m maximum thickness). The surface topography of each peat deposit shows several more or less coalesced peat domes with radial drainage out from the center. Tidal creeks receive drainage from the margins of both peat deposits where they are bordered by straits and estuaries. Because the base of the peat is generally at or slightly above high tide, the composition of the peat is unaffected by external sediments and marine or estuarine water.

Annual rainfall in this region of Sumatra is >2.5 m; rains are frequent throughout the year. Precipitation exceeds evapotranspiration, and the excess water from rainfall drains off and percolates through the peat domes. The absence of clastic sediment influx and the low concentration of dissolved solids input to the peat via rainfall result in the formation of low-ash peat. The dominant source of ash in the peat is the inorganic constituents concentrated by the plants. Our preliminary data show a relative increase in the ash content at the top, bottom, and margins of the peat deposits. Because of rainwater flushing, both peat deposits have a low-sulfur content even where they are adjacent to a marine environment. The ash and sulfur distribution in the peat is comparable to that of many coal beds.

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The acidity of the peat deposits restricts microbial degradation of the peat. The acidity decreases with depth from pH 3 in surface peat to pH 3–5 in basal peat in Siak Kanan and pH 4–6 in Bengkalis. Methane and possibly hydrogen sulfide were detected in some basal peats and in some sediments directly below the peat, especially in the Bengkalis peat deposit. This indicates that anaerobic methanogenic and sulfate reducing bacteria are active in the less acid basal peat and (or) in the organic-rich sediments below the peat. Preservation of some plant parts is excellent and hard wood is often encountered in the peat. The peat is predominantly fibric to fibric/hemic in texture. Highly decomposed sapric peat is uncommon and generally restricted to the base of the deposit. Peat accumulation rates are rapid, 4 m in ≈900 yr has been measured in the lower part of the peat profile in central Siak Kanan, indicating restricted degradation of the plant litter. Field observations indicate that facies exist within the peat deposits, and that these may be analogous to facies in coal deposits.

Domed tropical ombrogenous peat deposits, such as Siak Kanan and Bengkalis, may represent a type of modern analog for coal deposits that are characterized by low-ash and low-sulfur contents and are inferred to have originated in a tropical climate.

Estimation of Paleogeothermal Gradients and their Relationship to the Timing of Petroleum Generation, Eagle Basin, Northwestern Colorado

Vito F. Nuccio, Christopher J. Schenk, and Samuel Y. Johnson

Estimates of paleogeothermal gradients have been developed for three locations in the Eagle basin, northwestern Colorado, and the proposed timing of petroleum generation from an organic-rich source rock, the Belden Formation (Early and Middle Pennsylvanian) proposed. Levels of thermal maturity were determined by vitrinite reflectance (*Rm*) and calibrated with the Lopatin Time Temperature Index (TTI) modeling to determine paleogeothermal gradients. Different paleogeothermal gradient scenarios were used for each location, and "best fit" gradients which match TTI values with *Rm* values were determined.

The burial histories for the three localities are quite different, because during Pennsylvanian deposition, the three localities were in separate subbasins. Also, because of the variations in thickness of the overlying strata, the thermal maturity ranges from 2.50 percent at two of the locations to 3.70 percent *Rm* at the third. Depth of burial is not the only factor controlling the thermal maturity: geothermal gradients also differ for the three locations.

At one locality (Gilman), two paleogeothermal gradient scenarios have been postulated. The first scenario assumes a constant geothermal gradient of 1.80 °F/100 ft (32.9 °C/km) through time. In this case, the Belden Formation enters the oil window 275 Ma and leaves it 205 Ma. The second scenario assumes a changing paleogeothermal gradient; 2.30 °F/100 ft (42 °C/km) from 320 to 265 Ma, and 1.70 °F/100 ft (31.2 °C/km) from 265 Ma to present. Using this model, the Belden entered the oil window 284 Ma and left it 263 Ma. Both these models match the 3.70 percent R_m measured at Gilman with the corresponding TTI value of between 40,000 and 50,000.

At a second locality (Sweetwater), two models were used. The first assumes a constant gradient of 1.78 °F/100 ft (32.4 °C/km) through time and puts the oil window between 195 and 77 Ma. The second model assumes a gradient of 2.10 °F/100 ft (38.4 °C/km) from 320 to 265 Ma and a gradient of 1.70 °F/100 ft (31 °C/km) from 265 Ma to present, placing the oil window between 230 and 73 Ma. These models match the 2.50 percent R_m with the corresponding TTI value of approximately 2,700.

For a third locality (Glenwood), two models were again used. The first assumes a constant gradient of 1.87 °F/100 ft (34.0 °C/km) through time and puts the oil window between 168 and 75 Ma. The second scenario assumes a gradient of 2.60 °F/100 ft (47.4 °C/km) from 320 to 265 Ma and a gradient of 1.70 °F/100 ft (31.0 °C/km) from 265 Ma to present, placing the oil window between 245 and 75 Ma. These scenarios match the 2.50 percent R_m with the corresponding TTI value of approximately 2,700.

At all three localities, the rocks probably reached maximum thermal maturity during maximum burial between 68 and 65 Ma. As a result of the Laramide orogeny (approximately 65 to 37 Ma), the Eagle basin was uplifted and subsequent erosion led to "cooling"; hence, temperatures as great as those at maximum burial were never again reached. Tertiary intrusives emplaced south of the study area between 30 and 10 Ma probably had little or no effect on increasing the thermal maturity of the rocks.

The Campbell Creek/No. 2 Gas/Peerless/Powellton Coal Bed Correlation from the Middle Part of the Kanawha Formation of the Central Appalachian Basin

J.T. O'Connor

Coal geologists mapping coal resources in the Kanawha Formation of West Virginia have since the turn of the century defined two benches of the Campbell Creek coal bed: the Peerless bench and the No. 2 Gas bench. These two benches have more recently been mapped as separate beds and have even been distinguished from a third bed that has itself been named the Campbell Creek coal bed. All these names have been applied to and interchanged with the Powellton coal bed.

Discriminant analysis of major- and trace-element constituents of the Kanawha Formation coal beds has shown that groups of chemically related coal beds occur in zones separated by recognizable marine incursions. The chemical composition of coal beds from different zones generally varies more than that of coal beds from the same zones, although discrimination of some beds from within such zones is feasible. In this study we have classified the existing analyses of coal beds identified as being part of the Campbell Creek/No. 2 Gas/Peerless/Powellton coal group in an attempt to assist in the classification and gain information on the depositional environment of middle Kanawha time.

The four beds of this study occur in a single zone of the middle Kanawha, although some evidence exists for marine influence between the Powellton and the Campbell Creek coal beds. Detailed analysis of 51 samples of these coal beds in the USCHEM file of the National Coal Resource Data System (NCRDS) indicates that analyses attributed to the Campbell Creek, No. 2 Gas, and Powellton coal bed samples are more similar to each other than to analyses attributed to the Peerless coal bed samples (table 1). The elements that contribute most significantly to the variance of the data set were determined by principal component analysis to be five sets probably related to plant sources or argillaceous affiliations, a set probably related to sulfogenic sources, a set probably related to epigenetic marine influence, and two sets possibly related to source area chemistry or argillaceous affiliations. These elements account for 69 percent of the total variance of the data set encompassing the Kanawha, New River, and Pocahontas coal beds.

Considering the discontinuous nature of the deposition of the coal beds in this part of the Kanawha Formation and the use of unchecked existing names for the coal beds in question, this analysis may indicate a change in source area chemistry or depositional conditions between the lower and upper part of this coal zone or could be attributed to systematically unreliable geologic information in the USCHEM files. Combination of the analyses of the Peerless, Powellton, and other coal beds similarly situated in the Kanawha Formation and treating these coal beds as geologically and geochemically contiguous may assist in defining depositional environmental characteristics for the lower delta plain environment of the Pennsylvanian Period.

Table 1. Discrimination of the Peerless coal bed from the Powellton group of coal beds

Unit	Geologic environment	Discrim. character	Stat. signif.
Peerless coal bed.	Passive lower delta plain; occurs closely below Campbell Creek marine zone; often named as a bench of the Campbell Creek coal bed; may be thin (<1 ft thick), split, and discontinuous.	Hg v. high Lu high F high Ag high Br high	Moderate discrimination between groups at 100 pct for 51 samples; Wilks' lambda = .128 after 15 steps.
Powellton group (Campbell Creek, No. 2 Gas, Powellton coal beds).	Passive lower delta plain; occurs closely above Cannelton marine zone but below Peerless coal bed; often thin (<1 ft thick), split, and discontinuous.	SO_3 high Al_2O_3 high Hf low	

Selenium in Coal from the Powder River Basin, Wyoming and Montana

C.L. Oman, R.B. Finkelman, S.L. Coleman, and L.J. Bragg

Selenium (Se) in coal has attracted considerable attention as a potential environmental hazard, especially in many Western States, where environmental regulatory agencies require monitoring of selenium in overburden and spoil materials as well as in ground and surface water. Data stored in the National Coal Resources Data System (NCRDS) were used in this study to determine the geographic and stratigraphic distribution of selenium in coal samples from the Powder River basin, Wyoming and Montana. The samples used were primarily from the subbituminous coal beds in the Paleocene Tongue River Member of the Fort Union Formation. All concentrations are reported on a dry, whole-coal basis; the geometric mean for Se in 732 samples is 0.94 ppm. The maximum concentration detected was 12.6 ppm.

On a whole-bed basis, a distinct trend appears in the selenium distribution within the basin. Selenium concentrations decrease from 1.7 ppm south of lat 44° N. to 1.2 ppm in the central part of the basin between lat 44° and 45° N. to 0.7 ppm north of lat 45° N. The ash content of the coal also decreases from 12.5 weight percent in the south to 10.7 weight percent in the central part of the basin to 9.0 weight percent in the north.

Average selenium concentrations appear to be higher in younger coal beds; the younger Canyon coal bed has the highest average Se concentration (2.4 ppm) whereas the older Pawnee coal bed has the lowest concentration (0.7 ppm). Vertically within the Canyon coal bed, selenium, ash, organic sulfur, and pyritic sulfur correlate positively. The peak concentrations of these components show no vertical preference within the Canyon coal bed.

A positive statistical correlation exists between Se and ash ($r = 0.62$) for the 732 samples. The correlation of selenium with ash in the Powder River basin coal is stronger than the selenium–ash correlation in every other coal basin in the United States except the Denver basin. Selenium in the Powder River basin coals studied also correlates strongly with elements generally associated with detrital particles (such as Si, Al, K, Ti, La, Rb, Sc, Ta). In contrast, a poor correlation ($r = 0.3$) exists between Se and pyritic and sulfate sulfur. The correlation of Se with organic sulfur is weak ($r = 0.4$) in the southern and central parts of the basin but very strong ($r = 0.81$) in the northern part of the basin.

A chemical and mineralogical study of the mode of occurrence of selenium in selected coal and overburden samples in the Gillette, Wyoming, area indicates that selenium occurs in several chemical forms. Organically associated selenium may be the most common form of this element. Other modes of occurrence for selenium in these samples are (1) selenium-bearing pyrite, (2) lead selenide, (3) ion-exchangeable cation (perhaps associated with clays), (4) selenium-bearing galena, and (5) water-soluble forms (perhaps as selenate salts) commonly in oxidized sediments.

The seemingly paradoxical correlation of selenium with both ash and organic sulfur can be explained if the water transporting the detrital particles also carried dissolved selenium and sulfur into the Powder River basin. This suggestion is consistent with R.M. Flores' 1986 model postulating that these coal beds accumulated in swamps marginal to northerly-flowing streams. The decreasing ash content of the coal beds from south to north is also consistent with the concept that rocks south of the basin are the principal source of detritus. The source of the selenium may be seleniferous Cretaceous sedimentary rocks, such as the Niobrara Formation, which commonly crop out south of the basin.

Diagenetic Transformations and Phosphate Mineral Precipitation in Marine Lakes of the Palau Islands

W.H. Orem, W.C. Burnett[1], W.B. Lyons[2], W. Landing[1], and P. Chin[1]

Many island arcs consist partially or predominantly of uplifted carbonate reefs. These elevated limestone islands commonly contain marine lakes on stranded lagoons connected to the sea only through fissures and solution channels in the permeable rock. The stable environment and high productivity of these lakes make them ideal sites for studies of sedimentation and diagenesis. In addition, such marine lakes could be an environment in which some insular phosphate deposits were formed. Finally, many deep marine lakes on tropical islands are highly stratified and exhibit anoxic hypolimnia, making them ideal model environments for studies of geochemical processes across redox boundaries.

Our initial study of diagenetic processes and phosphate deposition in marine lakes focused on Jellyfish Lake, on the island of Eil Malk in the Palau Islands. This lake was chosen for study because (1) some background chemical and physical data on the lake appear in the literature; (2) the lake contains an anoxic hypolimnion and a bacterial mat at the redox interface; (3) some small phosphate deposits, possibly of subaqueous origin, are located on Eil Malk and elsewhere in Palau, allowing direct comparisons between phosphate minerals in lake sediments and nearby phosphorite deposits.

Sampling of the lake water and coring of the bottom sediments were carried out from a moored raft. On-site chemical analysis of the lake water and sediment pore water covered a number of parameters, including phosphate, ammonium, silicate, alkalinity, pH, chloride, fluoride, sulfate, and sulfide. Other analyses of the water samples and sediment studies (such as mineralogy,

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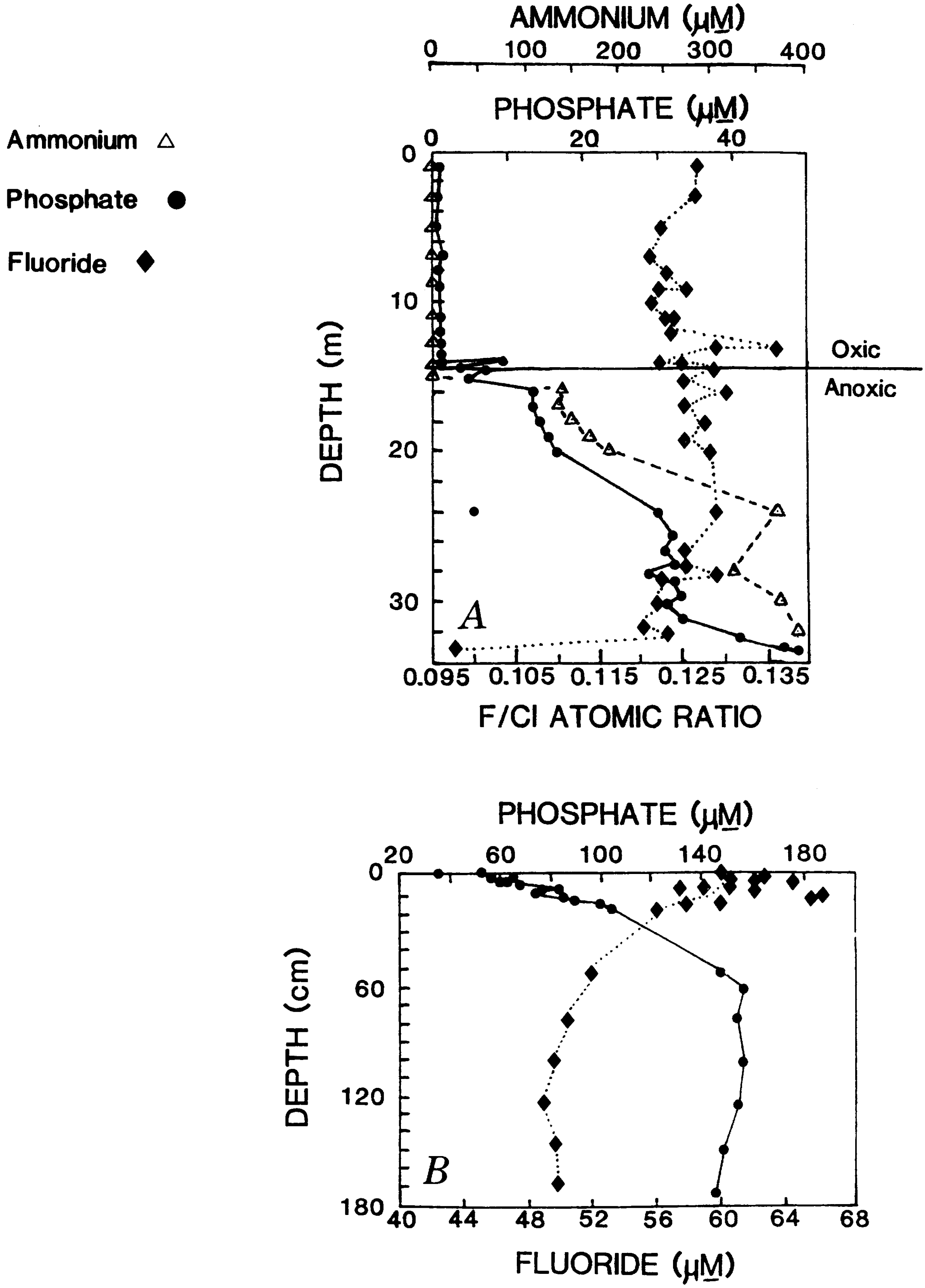

Figure 1. Overlying water and pore-water concentrations of ammonium, phosphate, and fluoride from Jellyfish Lake, Palau. *A*, overlying water values; *B*, pore-water values for these parameters. *μM*, micromolar.

radiochemistry, organic geochemistry, and major and trace elements) were reserved for laboratories in the United States.

Large changes in the concentrations of most chemical species were observed across the redox boundary (14–15 m), as shown in figure 1*A*. Phosphate and ammonium concentrations in the bottom water reached concentrations many times that in the surface water (40 and 400 times, respectively). Excess phosphate relative to total nitrogen was detected at the redox interface and just above the sediment/water interface. This excess phosphate probably resulted from the preferential degradation of organic phosphorus compounds by bacteria at these interfaces. (Similar excess phosphate concentrations have also been documented in pore waters of areas such as the Peru upwelling region, where phosphorite is known to be forming today.) Further evidence that phosphate minerals may be forming in these lakes comes from the pore water data (fig. 1*B*), which show a gradual decrease in fluoride concentration and a subsurface maximum in phosphate concentration. This loss of fluoride may be indicative of the formation of calcium fluorapatite minerals in the sediments. Mineralogical work will attempt to identify this phase in the sediments.

Organic geochemical studies have shown that the sediment is a mixture of algal and vascular plant residues and $CaCO_3$ debris. The proportion of organic residue originating from algae appears to increase with distance from shore. The major change in the organic matter with increasing depth in the sediments is loss of carbohydrates, as shown by ^{13}C nuclear magnetic resonance spectroscopy. However, substantial degradation of the organic matter even in the surface sediments, as indicated by a low carbohydrate content relative to fresh plant material, may have been caused by its long residence time in the water column prior to deposition. Studies are underway to identify specific biomarker compounds in the sediments and nearby phosphorite deposits in order to establish a genetic relationship.

The Association of Uranium with Organic Matter in a Uranium-Rich Peat Bog in the Carson Range Near Lake Tahoe, Nevada

W.H. Orem, R.A. Zielinski, and J.K. Otton

Uranium accumulates in surficial, organic-rich sediments of the Western United States and Western Canada where donor rock such as granite is being leached of uranium by shallow ground water. The organic-rich sediments are generally late Pleistocene to Holocene in age and are deposited along low gradients or ponded floors of stream valleys. The uranium is largely associated with the organic matter in these deposits, but the mechanisms of uranium entrapment are not well understood. We have investigated the nature of this association in the sediment and pore water of a small wetland, informally referred to as Upper Zephyr fen, located approximately 3 km east of Lake Tahoe on the west flank of the Carson Range. During August 1985, two cores each were obtained from two different sites in Upper Zephyr fen. One core from each site was reserved for pore-water studies, and a second core from each location was used for sediment studies.

The sediment in the fen extended to a depth of about 4.5 m; organic matter content ranged from 10 to 98 percent. The upper 3 m of sediment consisted mostly of a true peat, whose uranium content averaged 1,700 ppm (dry weight basis) but reached values as high as 5,100 ppm. Spectroscopic analysis of the peat using ^{13}C nuclear magnetic resonance spectroscopy (NMR) showed that the major change in the chemical structure of the organic matter is the loss of carbohydrates with increasing depth. A correlation between this loss of carbohydrates and the uranium content of the peat was not observed, indicating that the uranium may be associated with a more refractory component of the peat, possibly lignin or aliphatic residues.

In the pore water, uranium concentrations averaged about 42 ppb, but ranged to 95 ppb. These values were considerably higher than the overlying water value of 20 ppb uranium. Ultrafiltration revealed that 90 percent or more of the dissolved uranium is associated with high-molecular-weight compounds, indicating that it is probably associated with dissolved organic matter. Indeed, a strong correlation (r^2 = 0.931) was observed between dissolved organic carbon (DOC) and dissolved uranium in these pore waters (fig. 1). Studies underway will help to determine with what fraction(s) of the dissolved organic matter the uranium is associated.

Reconnaissance of Colorado Front Range Bogs for Uranium and Other Elements

Douglass E. Owen, R. Randall Schumann, and James K. Otton

Alpine bogs in the Colorado Front Range commonly form along spring lines in valley floors and in areas where drainage is restricted by moraines, slides, and beaver dams. The bogs generally lie between 7,000 and 10,000 feet elevation and are geologically young (late

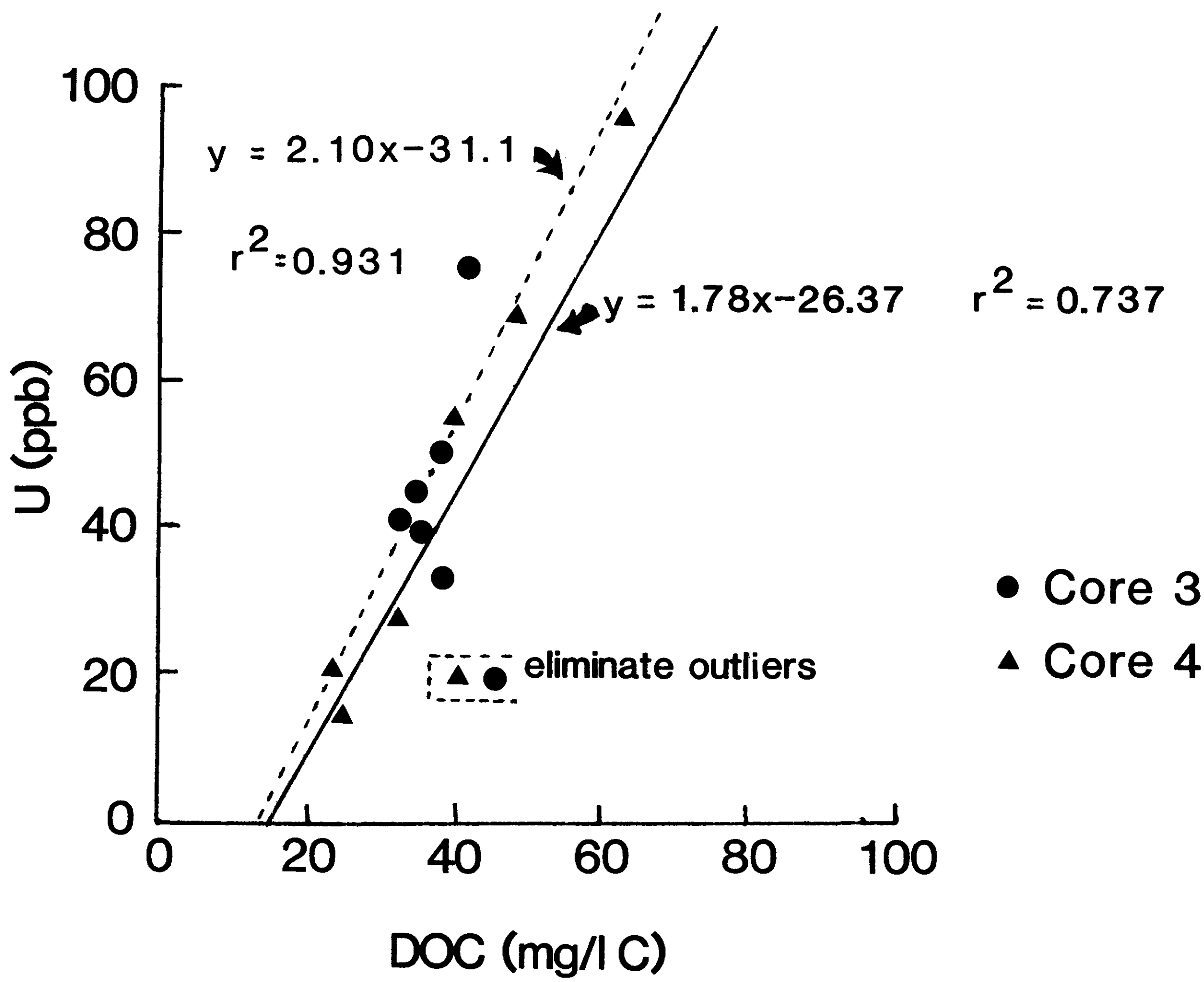

Figure 1. Pore water uranium versus DOC concentrations in two cores from Upper Zephyr fen. Two correlations are shown, one including all data with an r^2 value of 0.737 and the second eliminating two outlier points and having an r^2 value of 0.931. DOC in milligrams per liter carbon.

Pleistocene or early Holocene to late Holocene). The alpine bogs are also locally referred to as fens and commonly appear to be meadows from a distance. The bogs contain peat and organic-rich muck from a few decimeters to several meters thick. Peat has a great affinity for highly charged cations such as uranyl (UO_2^{2+}) that can be complexed and carried in local ground water. The geochemical enrichment factor between peat and uranium-bearing ground water can approach or exceed 10,000 to 1. As the bog sediments are geologically young, the uranium is in gross disequilibrium with its daughters, and the resultant low gamma radioactivity makes these occurrences undetectable by ground and aerial gamma ray surveys.

Reconnaissance auger sampling of bogs was conducted in the Colorado Front Range from the South Park area to the Colorado-Wyoming State line. Samples were dried and analyzed for elemental uranium and thorium using a delayed neutron activation technique. In addition, some of the samples were analyzed for 44 elements using ICP-OES (inductively coupled plasma-optical emission spectrometry). Most of the bogs have uranium concentrations in the 10–100 ppm range; however, samples from several of the bogs have uranium concentrations as high as 1,000–3,000 ppm on a dry weight basis. Some of the bog samples show concentrations of between 100 and 1,000 ppm for barium, manganese, strontium, and zinc. Bismuth, chromium, cobalt, copper, gallium, lead, nickel, tin, and vanadium were found in concentrations between 10 ppm and 100 ppm on a dry weight basis in some of the samples. These elements are not necessarily associated with high uranium concentrations.

Some of the bogs, in addition to being mined for peat, may contain enough uranium to be of commercial interest. Furthermore, uraniferous bogs are of environmental concern because of the previously unrecognized risk to local water quality. Uranium (and other metals) could be remobilized from the peat during interaction with acid mine drainage or during oxidation following a lowering of the water table or draining of the bogs.

Applying Aromatic Steroids to Determination of Thermal Maturity of Biodegraded Heavy Oils, Tar Sands, and Bitumens

James G. Palacas, Donald E. Anders, and J. David King

Petroleum explorationists have often experienced difficulty in determining the maturity and in turn the source of biologically altered heavy oils, tar sands, solid bitumens, and oil-stained rocks. Such biodegraded hydrocarbon deposits commonly are partially or totally depleted in standard geochemical fingerprints—such as n-paraffin and isoprenoid distributions, in particular pristane and phytane—thus rendering oil-to-oil and oil-to-source rock correlations difficult.

Using computerized gas chromatography–mass spectrometry, identification of specific biologic marker compounds permits reasonable assessment of the maturity and source of migrated oils. Our study focuses on the application of the monoaromatic-triaromatic steroid compounds as viable maturity indicators. The chief advantages of using aromatic steroids rather than other steranes or terpanes for maturity assessment are that (1) they are relatively more resistant to bacterial degradation and (2) collectively, aromatization reactions (transformation of monoaromatics to triaromatics) and triaromatic cracking reactions (conversion of high molecular weight components to lower molecular weight components) occur over a wider range of thermal maturities.

Using a combination of monoaromatic/triaromatic and triaromatic steroid ratios, we have determined semi-quantitative levels of thermal maturity for a variety of biodegraded oils occurring in different geologic settings. In the overthrust belt of western Greece, heavy oils from seeps were shown to have been derived predominantly from two sources: marginally mature and mature facies that may range in age from earliest Cretaceous to possibly Triassic. In the Tertiary lacustrine rocks of the Uinta Basin, Utah, the oils in tar sands at Sunnyside appear to have been derived from shallow, immature, or at best marginally mature source facies. In contrast, the oils in tar sands of the Permian White Rim Sandstone Member of the Cutler Formation, Tar Sand Triangle area, southeastern Utah, originated in relatively more mature organic facies than those at Sunnyside. Interestingly, the oils in the tar sands of the Triassic Moenkopi Formation, Vermillion Creek area, northwestern Colorado, have maturity signatures comparable to those in the Tar Sand Triangle area, indicating that the Moenkopi oils were also derived from source rocks of similar maturity.

Ideally, establishment of downhole profiles of aromatized steroid indices together with other maturity profiles (vitrinite reflectance, thermal alteration index (TAI), hydrocarbons/org C) in nearby wells could (1) assist in pinpointing more precisely the depth interval of the probable source facies, (2) permit correlation of the steroid indices to other viable maturity indicators, and (3) help evaluate the effect of source input, if any, on these aromatic steroid indices.

Trace-Element Analysis of Vitrinite Concentrates—New Approach for Determining Organic and Inorganic Affinity

Curtis A. Palmer, Paul C. Lyons, and Janet D. Fletcher

The chemical form (organic or inorganic) in which trace elements exist in coal is critical to the understanding of the chemical and physical processes of coal formation, such as the source of mineral species (for example, detrital, syngenetic), the processes of trace-element fixation, and mobilization of trace elements during coalification. A new method is proposed for classifying the trace-element affinities in coals using ratios of trace-element concentrations (TEC) in vitrinite concentrates (vit) and TEC in companion whole coals (cwc).

Twelve vitrinite-rich, medium- and high-rank mined whole-coal samples and corresponding vitrinite samples were analyzed for 37 elements by instrumental neutron activation analysis and d.c. arc spectrography. Generally, the ash contents of the vitrinite concentrates were less than 1 percent; in comparison, the cwc samples contained from 2.5 to nearly 40 percent. The associations of trace elements can be classified by the following elemental relationships:

1. $TEC_{vit}/TEC_{cwc} > 1$ indicates vit (organic) affinity
2. $TEC_{vit}/TEC_{cwc} = 1$ indicates either vit (organic) or cwc (inorganic)
3. $TEC_{vit}/TEC_{cwc} < 1$ indicates cwc (nonvitrinite) affinity

Chemically, the samples fall into two major divisions, low vitrinite affinity (2–7 elements) and high vitrinite affinity (10–13 elements) as illustrated in figure 1. These differences are probably due to variations among coal provinces, precursor plant components, paleoclimatic factors, and geochemical processes. Curiously, the only coals with high vitrinite affinity are the British coals and the Australian coal. Sodium (fig. 1) and magnesium (fig. 1) have vitrinite affinity in only one coal. (See p. 46 for fig. 1.)

A summary of organic and inorganic affinities, in order of decreasing organic affinity, for all samples in this study follows:

	Low vitrinite affinity Nine eastern U.S. coals Appalachian (6), Illinois (2) and Narragansett (1) Basins	High vitrinite affinity Three foreign coals Pennine (2 British) and Sydney (1 Australian) Basins
Always organic	Br	Br, As, Cr, Sb
Generally organic (> 67 pct of samples)	V, W	V, W, Ni, Cs, Hf, U
Organic or inorganic	B, Sb, Se, U, Zn	B, Ba, Se, Sr, Zn
Generally inorganic (> 67 pct of samples	Al, As, Ba, Ca, Ce, Co, Cr, Cu, Eu, Ga, Hf, Hg, La, Mg, Mn, Na, Ni, Rb, Sc, Si, Sm, Ta, Tb, Ti, Th, Yb	Al, Ca, Ce, Co, Cu, Eu, Ga, Hf, Hg, La, Mg, Mn, Na, Rb, Sc, Si, Sm, Ta, Tb, Ti, Th, Yb

Thermal Maturation of the Eastern Anadarko Basin, Oklahoma

Mark J. Pawlewicz

Thirteen wells were sampled in a profile across the eastern Anadarko basin, Oklahoma, from the northern shelf area near the Kansas State line, 125 miles (200 km) south to the deep portion of the basin in Caddo County, Oklahoma. Vitrinite reflectance measurements on these samples show that the level of thermal maturity of the sedimentary organic matter was set after maximum burial, by synorogenic heating.

Burial history reconstruction curves show the tectonic evolution of this area. Vitrinite reflectance measurements indicate temperatures higher than those generally accepted for the onset of hydrocarbon generation, and also higher than those found by other workers in the basin. Regression analysis yields a reflectance gradient of 0.109 percent R_m/1,000 ft (300 m). The 0.6 and 1.3 percent R_m isoreflectance lines define the interval of the oil window along the well profile. These lines can be used to estimate the level of thermal maturity of source rocks, and their volume. This information, in turn, can be used to estimate the volume of hydrocarbons generated by those rocks whose thermal maturity is within or above the oil window. Also, the generation potential of the thermally immature source rocks can be estimated by considering their volume above the 0.6 percent isoreflectance line.

Comparative Quality of the Upper and Lower Freeport Coal Beds in the Appalachian Basin

Brenda S. Pierce and Ronald W. Stanton

The Upper and Lower Freeport coal beds in west-central Pennsylvania consist of facies that are continuous over an area of 120 square miles and about 25 square miles, respectively. Each facies is distinct in its megascopic, petrographic, and washability characteristics. In the Upper Freeport coal bed, three coal facies (table 1, C, D, E) and one parting (LP) are continuous, and as many as five additional coal facies and one parting are discontinuous. In the Lower Freeport coal bed, four coal facies (C2, C3, C4, C5) and one parting (P2) are continuous, and one coal facies and one parting are discontinuous. (See p. 47 for table 1.)

These coal beds are interpreted to represent two types of peat formation in fluvial-lacustrine-swamp environments. In both swamps, peat began forming on a substrate of subaerially exposed limestone or flint clay. The lowermost facies of each bed (E and C5) have ash yields (table 1) resulting from finely laminated mineral-rich layers. These ash yields are attributed to intermittent detrital influx from adjacent stream channels that interrupted peat accumulation. In both settings, the detrital influx was areally extensive, covering the entire peat body and forming the clay-rich precursor to the lower partings.

After deposition of the partings, peat accumulation resumed and produced a series of facies in each bed. The Lower Freeport peat continued to evolve in much the same environment after deposition of the lower parting, forming a repetitive series of laterally extensive facies. The Upper Freeport, on the other hand, seems to have developed in different environments after deposition of the lower parting. Facies C and D have much higher vitrinite contents and lower inertinite contents than are found in the Lower Freeport facies. Facies C also has a much lower ash yield than the Lower Freeport facies. After the formation of facies C, fresh-water lakes formed over most of the swamp, terminating peat development in these areas. In the rest of the swamp, peat formation

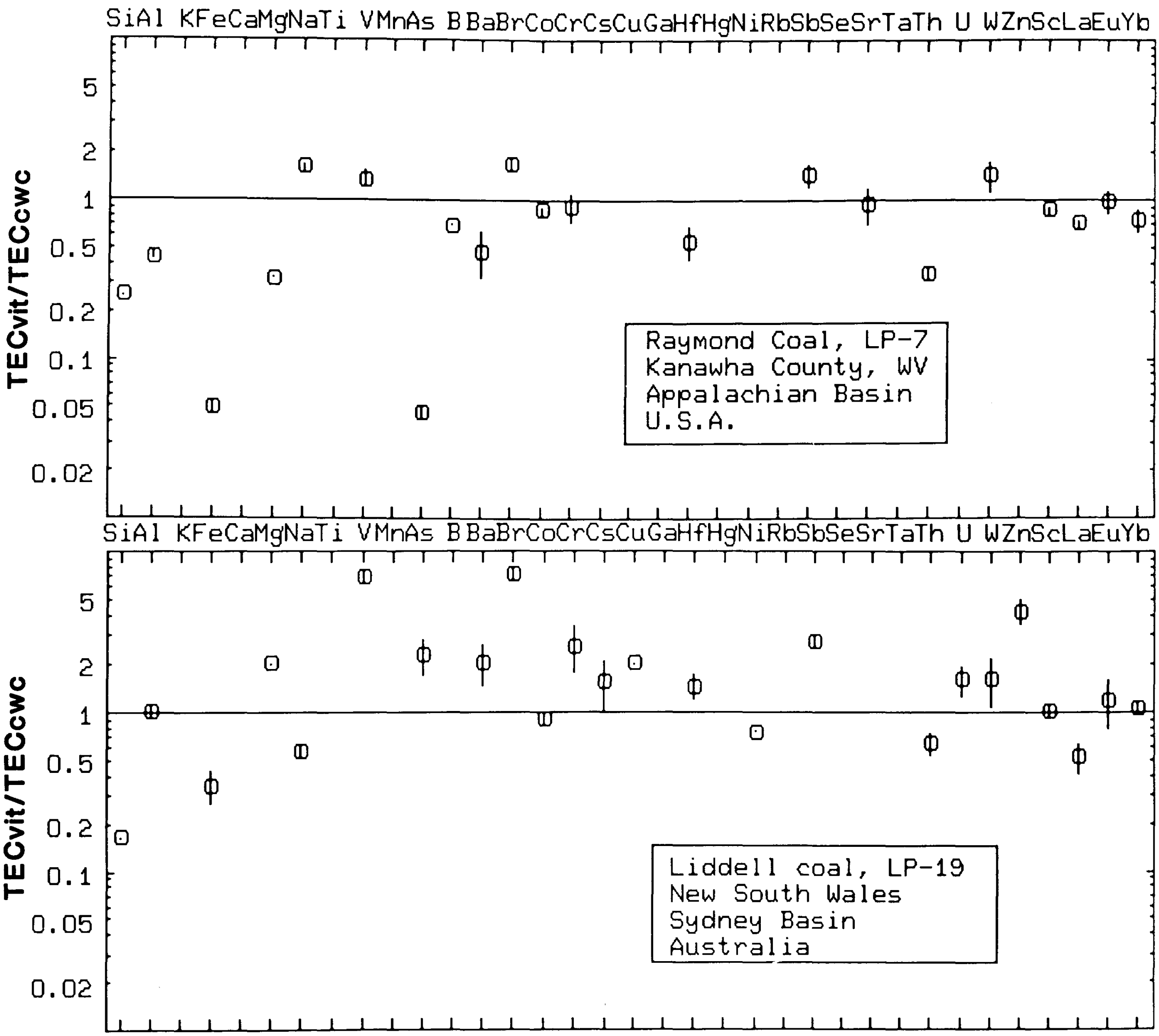

Figure 1. Comparison of TEC_{vit}/TEC_{cwc} ratios for a U.S. coal and an Australian coal. Error bars indicated by vertical line are based on instrumental activation analysis counting statistics. A single dot in center of symbol indicates element determined by d.c. arc spectrography. Elements not plotted are below detection limit in vit and (or) cwc.

continued locally as peat islands forming facies B, A', and A. These facies have much lower vitrinite contents and much higher inertinite contents than the rest of the coal bed.

That the physical and chemical nature of the peat in both swamps at the C3–C4 and C–D stages of formation inhibited inundation of the swamps is indicated by the restriction of the upper parting (P1) to the margins of the peat body. Furthermore, samples of C4 from the margins of the swamp have ash contents greater than 20 percent; the more interior locations have much lower ash yields (≤12 percent). The very low ash yields of facies C3 and C are also attributed to this restriction of detrital influence.

Although both coal beds formed in fluvial-lacustrine-swamp settings, the coal bed facies are different. The Lower Freeport developed a repetitive series of facies, whereas the Upper Freeport formed as a succession of different facies. The differences in quality and washability characteristics of these coal bed facies are related to variations in peat formation and associated mineral and maceral compositions.

Table 1. Quality data of the Lower Freeport and Upper Freeport coal beds

[Fac, facies; N, number of samples; Thk, thickness in inches; Ash, percentage ash; Sul, percentage sulfur; R 1.4, weight percent recovery at float 1.4 specific gravity; Vit, total vitrinite, mineral matter free basis; Int, total inertinite, mineral matter free basis; Ex, total exinite, mineral matter free basis; blank, no analysis run]

Lower Freeport									Upper Freeport								
Fac	N	Thk	Ash	Sul	R 1.4	Vit	Int	Ex	Fac	N	Thk	Ash	Sul	R 1.4	Vit	Int	Ex
C1	3	8.7	9.17	3.3	86.86	61	22	17	A	4	14.5	36.20	2.8		51	47	2
C2	6	16.0	11.99	2.3	78.54	60	20	19	A′	3	12.0	38.90	1.4		61	38	2
C3	6	15.2	9.11	1.2	87.85	68	16	15	B	7	20.0	12.24	2.3		72	26	2
P1		12.0							UP		7.0						
C4	5	11.9	17.73	1.1	59.76	75	9	16	C	21	28.0	6.99	2.4	89.19	86	10	4
P2		0.9							D	14	21.0	12.40	1.7	78.28	89	9	2
C5	5	13.9	12.17	0.7	78.11	64	18	17	LP		3.5						
									E	13	14.0	24.61	2.2	67.42	89	10	1

Preliminary Facies Analysis of the Sequence of Rocks Below the Upper Wyodak Coal Bed, Paleocene Fort Union Formation, Southeastern Powder River Basin, Wyoming

Frances Wahl Pierce and Edward A. Johnson

We conducted a preliminary facies analysis of as much as 646 ft of the rock sequence below the upper Wyodak coal bed, Paleocene Fort Union Formation, at three locations along the southeastern margin of the Powder River Basin, Wyoming. Channel, overbank sandstone, floodplain, and swamp facies are recognized. We believe these facies were deposited on an alluvial plain.

In the main study area, the channel facies is characterized by channel-form, fine to very fine grained sandstone bodies 10–50 ft thick that fine upward and have erosional bases. Lower parts of these bodies are trough cross stratified or convolute bedded. Upper parts generally consist of thin-bedded sandstone with rare, poorly developed ripple laminations and mudrock partings. Paleocurrent measurements indicate sediment transport to the north and west.

Interchannel areas are represented by the three remaining facies noted. The overbank sandstone facies is represented by fine to very fine grained tabular beds about 1–7 ft thick. Basal contacts are generally sharp and upper contacts are sharp to gradational. Lower parts of these beds are usually featureless; upper parts are parallel laminated or display poorly developed ripple laminations. Burrows, fluid escape structures, and weakly developed paleosols are also present. We interpret the overbank sandstone facies to represent crevasse splay or sheet flood deposits. The floodplain facies consists primarily of rooted gray mudrock 1–30 ft thick with zones of ironstone concretions. The mudrock is commonly laminated and contains abundant fossil plant debris. This facies accumulated on a floodplain that was probably permanently saturated by a high water table. The swamp facies consists of brown to black carbonaceous shale 1–17 ft thick and coal beds 1–7 ft thick.

In outcrop, these facies occur in laterally continuous zones that we call sandstone-dominated and mudrock-dominated complexes. These complexes are arranged vertically in an alternating sequence, possibly reflecting the migration of meandering fluvial channels across the alluvial plain.

Eleven miles to the north and 13 mi to the south, additional outcrop studies identified similar facies in the interval below the upper Wyodak coal. To the north, the facies occur in almost the same proportion as in the main study area, but to the south, facies of the interchannel areas are much more common than the channel facies. In neither outlying area can we recognize sandstone-dominated complexes as we can in the main study area. We believe that the changes in facies proportion and arrangement can be explained by different depositional processes operating in each of the three areas.

By analyzing facies and interpreting the environment of deposition, we are beginning to reconstruct the paleogeography of part of the southeastern Powder River Basin just prior to the accumulation of peat that resulted in the economically important Wyodak coal deposit. By understanding the conditions preceding the accumulation of this peat, we are gathering information that will enable us to design a model depicting the origin of the deposit. Such a model could be used by the mining industry to help develop exploration and mining plans.

Diagenetic Evolution of Deep Hydrocarbon-Bearing Rocks in the Ordovician Simpson Group, Anadarko Basin, Oklahoma—Evidence from Mineralogic, Stable Isotope, and Fluid Inclusion Studies

Janet K. Pitman and Robert C. Burruss

The Simpson Group in the southeastern Anadarko basin consists of transgressive-regressive cycles of interbedded sandstone, carbonate, and mudstone deposited in a shallow marine environment in the southern Oklahoma aulacogen. Submature to supermature quartzarenites and immature subarkoses, at present burial depths of 11,000–17,000 feet, display two stages of petroleum migration and a complex diagenetic history involving (1) precipitation and dissolution of iron-free and iron-bearing carbonate, (2) formation of abundant authigenic quartz, and (3) development of a clay mineral assemblage. Combined petrographic, stable isotope, and fluid inclusion data in conjunction with the modelled reconstructed burial and thermal history of the basin permit interpretations of the paragenetic sequence.

The earliest diagenetic stage is represented by rare occurrences of dead oil that locally fills primary pores, occurs between quartz grain and grain overgrowths, forms a thin film on incompletely developed quartz overgrowths, and is disseminated as opaque inclusions in carbonate cement. In a few samples, rare fluorescent oil inclusions are trapped at the dust rim between detrital grain and grain overgrowth. The first stage of oil migration, during early burial, preceded mechanical compaction or significant diagenetic alteration that preserved the sandstones from further diagenetic modification. Iron-free, pore-fill calcite, partially replaced by ferroan calcite, also precipitated at shallow burial depths before grain compaction or the development of quartz overgrowths. Both varieties of calcite show the effects of dissolution possibly caused by organic acids and CO_2 released during catagenesis. Authigenic illite and chlorite commonly fill secondary pores that resulted from the leaching of calcite. Late in the diagenetic history during deep burial, zoned, rhombic, iron-bearing dolomite, in many places containing inclusions of oil, selectively replaced calcite and iron-rich clay. Isotope geochemistry of early- and late-formed carbonate shows enriched $\delta^{13}C$ compositions characteristic of marine carbonate with little or no input from organic carbon. $\delta^{18}O$ values are depleted, possibly reflecting increased temperatures due to greater burial depth; the original oxygen isotope composition of waters buried with the sediments likely approximated that of seawater. Well-developed quartz overgrowths are pervasive in quartzarenites, except in areas where carbonate cement or hydrocarbons were introduced during early burial. Secondary quartz formed during moderate burial after framework grain compaction, effectively eliminating most porosity in the deepest sandstones. A late stage of petroleum migration is documented by stylolitic seams and fracture surfaces stained by dead oil. In some samples, fluorescent oil inclusions are trapped on microfractures that crosscut grain boundaries and overgrowths and terminate at stylolites. This second stage of petroleum migration occurred in response to deep burial and associated regional deformation during the Pennsylvanian age Ouachita orogeny.

Banks, Reefs, Deltas, and Fans—Jurassic-Cretaceous Transition in the Baltimore Canyon Trough

C. Wylie Poag, John S. Schlee, B. Ann Swift, Mahlon M. Ball, and Linda Sheetz

The last 10 years have seen a burst of information regarding the regional structure and depositional patterns of the Baltimore Canyon trough. Early, rather generalized interpretations were based chiefly on seismic-reflection profiles. To this seismic data base have gradually been added geologic data from 34 exploratory wells, 18 intermittently cored holes on the continental shelf, and 11 continuously cored holes on the continental slope and rise. Acquisition of high-resolution seismic profiles, reprocessing of older multichannel profiles, and refinement of biostratigraphic interpretations now allow a fine-scaled reassessment of the geologic evolution of this basin. We have begun this second-stage analysis by focusing on the Jurassic-Cretaceous transition.

The Late Jurassic (Tithonian-Kimmeridgian) outer continental shelf in the Baltimore Canyon trough was a broad carbonate platform, bordered off New Jersey by a pinnacled barrier reef. The reef complex is structurally highest off southern New Jersey, is lower to the north, and is breached by a broad, 2-km-deep channel off Ocean City, Maryland. Landward of the reef tract, a series of parallel, southeastward-dipping, listric, normal faults (the Gemini fault system) break the Jurassic outer shelf into a series of elongate, tilted blocks, some characterized by rollover anticlines on the downthrown sides. This faulting is the result of loading the shelf edge with 4 km of post-Jurassic sedimentary rocks. The other principal structure is a large igneous intrusion (Schlee Dome), whose flanks have been drilled by several petroleum tests. Upper Jurassic strata have been eroded to < 100-m thickness across the crest of Schlee Dome.

At the shelf edge, a precipitous reef face (25° slope) rises as high as 2 km above the adjacent Late Jurassic continental rise. A 2-km-thick wedge of reef talus and slope-front fill spreads eastward across the deep-sea basin (North American basin), thinning on the lower rise to < 50 m where it was drilled at DSDP Site 105.

Following a period of lowered sea level and presumed subaerial exposure, during which the southern part of the reef tract was breached, Early Cretaceous (Berriasian and Valanginian) siliciclastics began to accumulate in a thick deltaic wedge behind the shelf-edge carbonate barrier. To the north, where the barrier was lowest, and at the breach, the Lower Cretaceous debris buried the Jurassic shelf-edge carbonates and spilled out onto the continental rise as debris flows and turbidity currents. That some of these terrigenous components spread as far as 500 km southeast of the breach is shown at DSDP Site 603, in which 100 m of coaly, sandy mudstone and marly limestone was cored.

Early Cretaceous depositional rates were maximal in a large deep-sea fan off northern New Jersey, and in the breach off Ocean City, Maryland, where more than 2 km of Berriasian and Valanginian sediments accumulated in 13 m.y. (15 cm/1,000 yr; uncorrected for compaction). The reef complex remained a barrier to basinward sediment transport off southern New Jersey, however; depositional rates seaward of the shelf-edge were no greater than 4.5 cm/1,000 yr.

Relationship of Clay-Mineral Diagenesis to Temperature, Age, and Hydrocarbon Generation— An Example from the Anadarko Basin, Oklahoma

Richard M. Pollastro and James W. Schmoker

The work reported here relates the diagenesis of interstratified illite/smectite (I/S) to burial history and oil generation and tests the dependence of temperature and time on the smectite-to-illite reaction.

Clay mineralogies of shales and sandstones of Morrowan–late Springeran age (Early Pennsylvanian) were determined by X-ray powder diffraction (XRD) of core samples from a 13-well profile extending northwest to southeast across the Anadarko basin, Oklahoma. I/S clay, as defined by XRD patterns, is abundant in both the shales and sandstones. Randomly interstratified I/S occurs in many of the shallow samples, but disappears in the present-day depth range of 2,750–3,050 m; only ordered I/S is found in samples below 3,050 m. A regional vitrinite-reflectance profile compiled for the Anadarko basin suggests an average erosional removal of about 800 m. Therefore, maximum burial depth of the zone where randomly interstratified I/S disappears is about 3,540–3,840 m.

Published temperature models suggest that, for Tertiary and Cretaceous rocks, the transition from randomly interstratified I/S to short-range ordered I/S occurs between 100 and 110 °C. Assuming a constant geothermal gradient of 2.37 °C/100 m and burial histories as shown in figure 1, maximum temperatures of 100–110 °C correspond to present-day burial depths between 2,700 and 3,120 m. These independently calculated depths for the 100–110 °C isotherm are in excellent agreement with the depths at which randomly interstratified I/S is observed to disappear in Morrowan-Springeran age rocks. The similarity in temperature for the I/S phase change in rocks of Early Pennsylvanian, Cretaceous, and Tertiary age spanning a time of some 300 million years suggests that time plays a secondary role in the diagenesis of these clay minerals.

The relation between the I/S transition and oil generation in the Anadarko basin is shown in figure 1. The nonparallel bands illustrate the different time dependence assumed for kerogen maturation and clay diagenesis. The burial histories of two areas in the basin (*A* and *B*, fig. 1) illustrate how clay-mineral diagenesis at these locations can be related to stages of hydrocarbon generation, the time and tectonic period at which clays entered critical temperature windows, and the length of time spent at or above critical temperatures.

Potential Petroleum Source Rocks in the Late Proterozoic Chuar Group, Grand Canyon, Arizona

Mitchell W. Reynolds, James G. Palacas, and Donald P. Elston

The Chuar Group, upper part of the Grand Canyon Supergroup in northwestern Arizona, is a 1,637-meter-thick succession of predominantly very fine grained siliciclastic rocks that contains thin sequences of sandstone and stromatolitic and cryptalgal carbonate rocks. More than half the succession consists of organic-rich gray to black mudstone and siltstone; fossil microorganisms are abundant to common throughout successions of dark mudstone and siltstone.

Strata of the Chuar Group likely accumulated in a succession of environments that included a sediment-starved basin rich in organic material, a coastal or alluvial plain, and mixed coastal or paludal swamp and alluvial

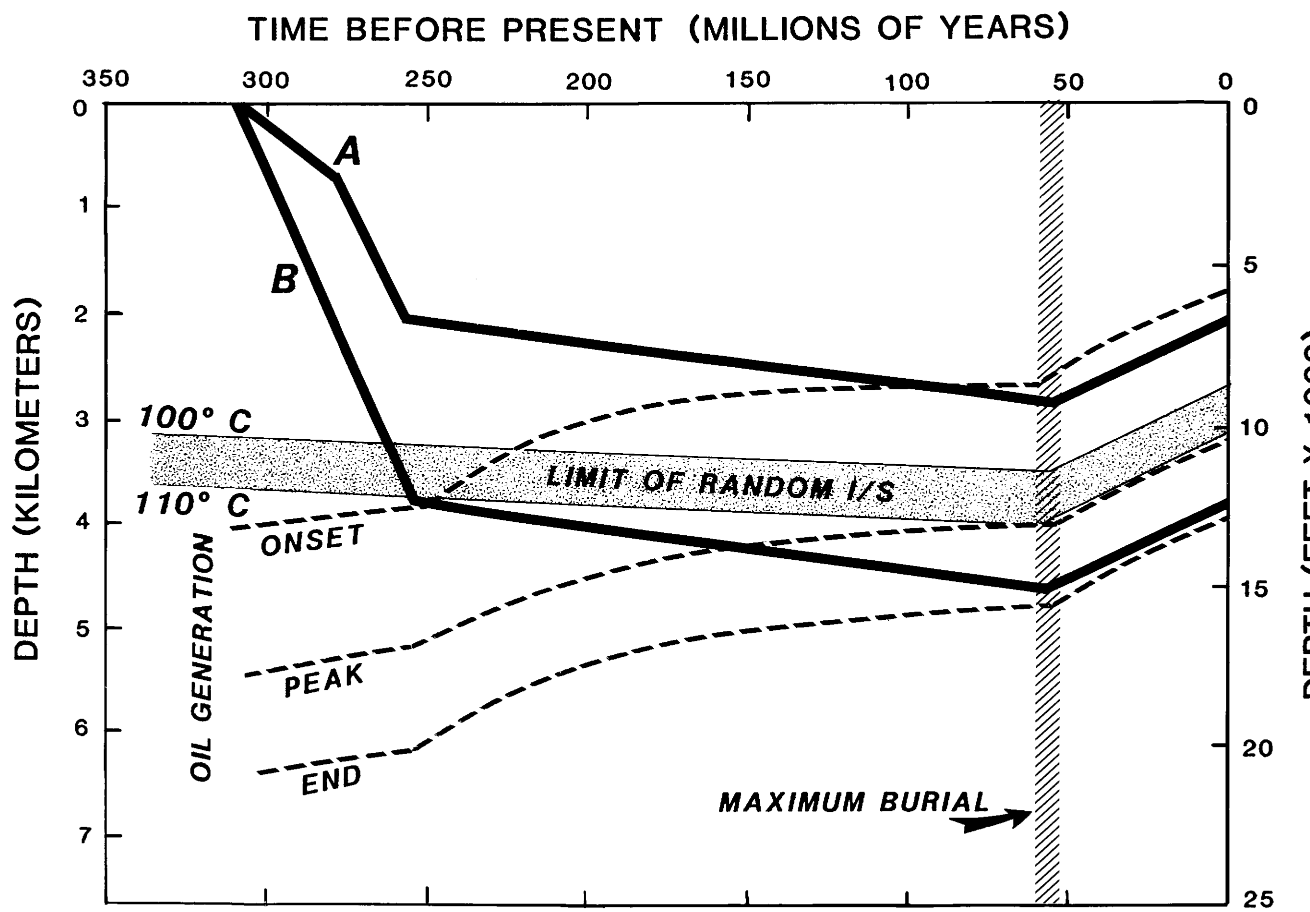

Figure 1. Lopatin, burial, and temperature reconstructions for Morrowan rocks, Anadarko basin, Oklahoma, relating ordering changes in interstratified illite/smectite (I/S) to burial history and the oil window. Solid lines are burial reconstructions for top of Morrowan near wells with (*A*) randomly interstratified I/S and (*B*) only ordered I/S. Dashed lines are time-depth reconstructions for oil generation based on Lopatin modeling. Mottled zone shows 100–110 °C temperature band and represents predicted upper limit for randomly interstratified I/S.

plain environments. Stromatolitic, cryptalgal, oolitic, and pisolitic carbonate rocks demonstrate nearshore aqueous environments. Depositional sequences of aqueous and subaerial settings alike seem to be markedly cyclic.

In the past, the site of deposition has been interpreted as a foundering marine embayment on the passive edge of the continent. The character and succession of the strata, in conjunction with new possible correlations with Late Proterozoic rocks of probable marine origin in adjacent parts of the Western United States, suggest the alternate hypothesis that Chuar strata accumulated in a lacustrine setting in a subsiding region within the continent.

Preliminary analyses indicate that dark mudstone from the Chuar Group contains as much as 5 percent total organic carbon. Rock-Eval T_{max} values, generally ranging from 430 to 440 °C, indicate that the rocks, particularly in the upper part of the succession, are within the principal oil-generating window. Hydrogen index (HI) values of as much as 190 $mgHC/gC_{(org)}$, and genetic potentials (S_1+S_2) of as much as 6 kg/ton (6,000 ppm) demonstrate that the rocks still have potential for generating sufficient amounts of gaseous and liquid hydrocarbons for commercial accumulations.

Chuar Group strata, now exposed only on the north side of the Colorado River in the eastern part of the Grand Canyon, plunge north beneath the Kaibab Plateau of Arizona and southwestern Utah. In the Grand Canyon the strata are truncated on the east by a normal fault that predates the Cambrian Tapeats Sandstone. We suggest that if the Chuar Group is present more widely beneath Phanerozoic rocks of the Kaibab Plateau or is preserved in pre-Phanerozoic grabens in northern Arizona or southern Utah, the strata may have served as source rocks for potential petroleum accumulations in lower Paleozoic or Proterozoic units yet to be prospected in that region.

Relation of Major Sea-Level Fall and Regional Unconformity to Hydrocarbon Accumulations, Upper Cretaceous Turner Sandy Member of Carlile Shale, Black Hills Uplift

Dudley D. Rice and C. William Keighin

The Upper Cretaceous (Turonian) Turner Sandy Member of Carlile Shale forms a large lobe of interbedded sandstone, siltstone, and shale that extends eastward across the Black Hills uplift of northeastern Wyoming, western South Dakota, and southeastern Montana. The sediments were deposited on the shallow, flat, western shelf of a north-south-trending epicontinental seaway. The sediments were transported to shelf by a major river-dominated delta system located in southwestern Wyoming. The Turner lies above the Pool Creek Member of the Carlile Shale, on a regional unconformity that resulted from marine erosion during global sea-level fall in middle Turonian time.

The Turner Sandy Member consists of two sandstone intervals separated by shale. The lower interval, which lies directly on the marine erosional surface, is as much as 7 m thick and is composed of two types of sandstone. One type, medium grained, occurs as tabular and cross-stratified sets as much as 1 m thick. Paleocurrent measurements indicate a general eastward direction of transport. These sandstones filled erosional lows in underlying marine shale during sea-level rise. Within this medium-grained sandstone are conglomeratic lenses containing shark and ray teeth, fish vertebrae, shell hash, shale rip-up clasts, wood fragments, and pebbles and granules of chert. These lenses are transgressive lags. The other type of sandstone in the lower interval is very fine to fine grained, displays planar lamination, wave-ripple cross-lamination, and some hummocky cross-stratification, and has a sharp base with occasional sole marks. This type accumulated as more widespread sandstone bodies in a shelf environment that was occasionally affected by storm activity.

On the south flank of the Black Hills uplift, the upper sandstone interval consists of two thin (1.5 m average thickness) very fine grained sandstone units that are made up of individual beds intercalated with shale or amalgamated. Each bed has a sharp erosional base with sole marks and grades upward into shale. Hummocky cross-stratification is the dominant type of stratification. Wave-ripple cross-stratification is commonly developed at the tops of beds or units where beds are amalgamated. Trace fossils of *Cruziana* ichnofacies are restricted to rippled surfaces. Lenses and concretions of shells of ammonites and bivalves occur at the base of units.

On the west flank of the Black Hills uplift, the upper sandstone interval is as much as 7 m of very fine grained sandstone with decreasing intercalations of shale upward in the lower part. Planar lamination and hummocky cross-stratification are prevalent in the lower part. The upper part is thoroughly bioturbated by trace fossils of *Skolithos* ichnofacies. The upper sandstone unit at both sites was deposited below fair-weather wave base on a storm-wave dominated shelf. On the south flank of the uplift, the upward sequence of sedimentary structures in individual beds suggests a decrease in energy level, indicating waning of storm activity and return to fair-weather conditions. On the west flank, deposition above fair-weather wave base is suggested in the upper part by bioturbation of *Skolithos* ichnofacies.

Several oil fields have been discovered in the lower sandstone interval of the Turner Sandy Member on the southwest flank of the Black Hills uplift. The reservoir is composed of beds of medium-grained sandstone that are confined to narrow east-west channels that resulted from sea-level fall and erosion of underlying marine shale. Both sandstone intervals are potential reservoirs for biogenic gas on the north, east, and south flanks at uplift where mature source rocks are not present.

Identification and Importance of Coal Bed Gas, San Juan Basin, Southwestern Colorado and Northwestern New Mexico

Dudley D. Rice, Charles N. Threlkeld, and April K. Vuletich

Coal beds are considered to be a major source of nonassociated gas in the Rocky Mountains. In the San Juan Basin, northwestern New Mexico and southwestern Colorado, significant quantities of natural gas are being produced from coal beds of the Upper Cretaceous Fruitland Formation and from adjacent sandstone reservoirs. Analysis of gas samples from the various producing intervals provides a means of determining their origin and of evaluating coal beds as source rocks.

The rank of coal beds in the Fruitland Formation, where major production occurs, increases from southwest to northeast: it ranges from high-volatile bituminous A to medium-volatile bituminous (R_o values 0.7–1.4 percent). On the basis of chemical and isotopic composition and coal rank, the gases produced are interpreted to be thermogenic. Gases from the coal beds show little isotopic variation ($\delta^{13}C_1$ values -43.0 to -40.5 ppt), are chemically dry (C_1/C_{1-5} values 0.98–0.99), and contain significant amounts of CO_2 (as much as 6 percent). These gases are interpreted to result from devolatilization, which yields methane, carbon dioxide, and water as the primary products. In contrast, gases from sandstones in the Fruitland Formation and underlying Pictured Cliffs Sandstone have a wider range of isotopic values ($\delta^{13}C_1$ values -43.9 to -39.0 ppt), are chemically wetter (C_1/C_{1-5} values 0.86–0.94), and contain less CO_2 (<2 percent); these sandstones also produce minor amounts of waxy, immature oil. These gases are interpreted to have been derived from nonmarine kerogen (Type III) dispersed in marine shales of the underlying Lewis Shale and in nonmarine shales of the Fruitland Formation.

These two gas types are distinctly different from that of gases associated with oil produced from the underlying Upper Cretaceous Dakota Sandstone and Tocito Sandstone Lentil of Mancos Shale. This associated gas is isotopically lighter and chemically wetter at equivalent levels of thermal maturity than those derived from coal and dispersed Type III kerogen. This gas is interpreted as a product of thermal cracking of marine kerogen (Type II).

Some gas samples from sandstones in the Fruitland Formation and Pictured Cliffs Sandstone are almost identical in chemical and isotopic composition to those from coal beds in the immediate area. These samples probably represent gas that migrated from nearby coal beds into the sandstone.

Three types of gas have been identified on the basis of chemical and isotopic composition in the San Juan Basin: those generated from (1) Type II kerogen, (2) dispersed Type III kerogen, and (3) coal beds. Most of the coal-derived gas is contained within coal beds, indicating that expulsion into adjacent sandstone reservoirs has not taken place.

GLORIA Survey off the East Coast of the United States

J.M. Robb, D.W. O'Leary, W.P. Dillon, P. Popenoe, E.A. Winget, J.S. Schlee, D.C. Twichell, P.C. Valentine, and K.M. Scanlon

From February through May 1987, the U.S. Geological Survey and the Institute of Oceanographic Science (United Kingdom) conducted a long-range sidescan-sonar survey of the Exclusive Economic Zone (EEZ) off the United States East Coast. The acoustically derived images of the sea floor have been assembled into a preliminary regional mosaic of the sea bottom extending from the Florida Peninsula to Georges Bank and the Scotian Shelf.

The continental slope off New England is deeply etched and eroded; much of the continental rise area is covered by fairly uniform sheets of debris below 2,500-m water depth. Discrete groups of canyons that incise the slope converge to form single channels on the upper rise, most of which are choked by debris. Only five of the canyons that indent the shelf extend as far as the boundary of the EEZ; all five maintain their sinuous, incised character for great distances. Some canyons are linked in a crude reticulate pattern that suggests sea-floor tilting or fracturing. Sheets of debris surround Picket, Retriever, and Buel Seamounts. All of the New England Seamounts are at least partially buried, and their surfaces are greatly eroded.

Off the Middle Atlantic States, the GLORIA images show the sharply bounded compartments of the continental rise, each dominated by a distinct set of processes. Immense areas of bottom failure and landslide alternate with areas of smooth deposition. Submarine channels, some cut deeper than 300 m below the sea floor, cross the ocean floor for more than 160 km. Between Baltimore and Toms Canyons, canyons and curving channels in a vast dendritic pattern join to form a single large channel that extends to the border of the EEZ.

The exceptionally steep continental slope in the Cape Hatteras area is characterized by bands of outcropping strata that are cut by submarine canyons and massive slumps. South of Cape Hatteras, the slope angle decreases, and the slope is increasingly covered by younger sands and muds of Quaternary age.

Surface manifestations of diapiric structures have been identified off the Carolinas and off New Jersey in preliminary mosaics. The Albemarle Slump and another slide off Cape Romain are clearly visible on the data. The sonographs have mapped a third slide, previously unknown and equally large, between them. Long rubble trains descend from these slumps and are traceable beyond the 200-mile limit of the EEZ.

Several of the canyons off the Carolinas are now known to make abrupt, right-angle turns into a large, transverse canyon that parallels the coastline and acts as a conduit to the deep sea. A ridge seaward of the transverse canyon is covered by massive ripple-like features 75 m high and 5 km from crest to crest that indicate northeastward sediment movement.

In the Blake Escarpment area off eastern Florida, the mosaics show a 100-km-long current-scoured depression extending south from the base of the Blake Spur. In the lee of the spur, where the escarpment is protected from the strong southward flow, a previously unknown set of submarine canyons cuts into the escarpment. On the Blake Plateau, Gulf Stream-scoured exposures of older strata end abruptly at the crest of the "Charleston Bump," where the shelf appears to be covered by a sand sheet that is marked only by scattered deepwater reef pinnacles. Individual reefs are nearly 1.6 km wide and as high as 45 m.

The GLORIA surveys also gathered correlative data in the form of echo-sounding, magnetic intensity, and high-resolution seismic-reflection profiles along track. The data assemblage is combined with known seismic and sampling data. These interpretive geologic compilations are released to the public in atlas format, usually within a year of data collection. The atlas for the Pacific coast was published in 1986, and for the Gulf of Mexico and the Caribbean in 1987.

Manganese Binding by Iron Bacteria in Wetlands—A Potential Analog for Manganese-Rich Coal

E.I. Robbins, E.W. de Vrind,[1] Hans de Vrind,[1] and W.C. Ghiorse[2]

A study of iron bacteria in modern wetlands reveals rodlike and doughnut-shaped mineral precipitates that may be identifiable in the fossil record. Wetlands that are fed by anoxic ground water carrying reduced species of Fe(II) and Mn(II) are populated by manganese-binding and manganese-oxidizing iron bacteria. Iron bacteria, the group of bacteria that precipitate iron oxides, can be abundant and highly visible in wetlands that have iron in their watersheds; the water is often bright red. The dynamics of bacterial precipitation of both iron and manganese are quite complex, and not all steps in the metabolic pathways are understood or proven. Whether the oxidation of Fe(II) or Mn(II) serves as an energy source or as a detoxification mechanism, the end product is microbially precipitated iron and manganese.

An important species of iron bacteria that can precipitate both metals is *Leptothrix discophora*. In wetlands, *L. discophora* often forms oil-like films on water. Its filaments have expanded ends which serve as flotation disks that attach at the air-water interface. The surface film can be collected on a glass slide; microscopic examination reveals the presence of characteristic rodlike sheaths and doughnut-shaped holdfasts. The mineralized sheaths of iron bacteria have been found to contain the hydrated iron oxide, ferrihydrite, a metastable mineral that can dehydrate to form hematite. The coated sheaths also may contain manganese oxides.

Manganese-binding iron bacteria have been studied in three wetland areas in Northeastern United States. Several strains of *L. discophora* that appear to produce manganese-oxidizing proteins associated with polysaccharide-protein exopolymers have been isolated from Sapsucker Woods Swamp in Ithaca, New York. The protein of strain SS-1 has a molecular weight of 110,000 and is inactivated by treatments such as exposure to temperatures higher than 80 °C, detergents, and heavy metals, as shown in a 1986 study by L.F. Adams III. It catalyzes the reaction: $Mn^{2+} + \frac{1}{2} O_2 + H_2O - MnO_2 + 2H^+$, obeying Michalis-Menton kinetics suggesting that the manganese-oxidizing protein is a bacterial enzyme.

The water of Bear Trap Creek in Syracuse, New York, is bright red from the presence of films of *L. discophora*. The *L. discophora* strain from this water loses its sheath-forming ability upon culturing in rich media; part of its manganese-oxidizing activity is excreted into the medium. It contains at least two proteins with manganese-oxidizing activity, as detected with sodium dodecyl sulfate-gel electrophoresis.

The Huntley Meadows wetland near Mount Vernon, Virginia, has extensive areas where ground water discharges Fe(II) and Mn(II). The iron bacteria of this wetland, *Leptothrix discophora*, *Leptothrix/Sphaerotilus* sp., *Gallionella*, and *Siderocapsa*, all oxidize manganese. Manganese oxide also precipitates on slimy rocks at the break in slope between the iron-rich rocks of the Cretaceous highlands and the Pleistocene sediments of an old Potomac River meander scar where the wetland is located; mini-nodules of manganese oxide can be collected in certain reaches of the streams. We have not attempted to isolate the bacteria on the rocks, but submerged glass slides in these reaches become coated with the doughnut-shaped precipitates characteristic of *L. discophora*.

Wetlands that deposit peat and are fed by ground water may be useful modern analogs for manganese-rich coal. Manganese-bearing coal, such as those in Alabama, Colorado, and Iowa, may be the remains of wetlands where microbial populations bound manganese and iron into minerals that can be recognized as microbial in origin.

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Coal Quality and Distribution in Upper Cretaceous and Tertiary Rocks, East-Central North Slope, Alaska

Stephen B. Roberts

Extensive coal deposits underlie a region of greater than 4,000 square miles on the east-central North Slope of Alaska. The coal-bearing strata, which include rocks of both the Upper Cretaceous Prince Creek Formation and the Tertiary Sagavanirktok Formation, have been interpreted as part of a time-transgressive deltaic sequence which prograded generally northeastward. Previous workers have estimated the coal resources of this region to be 50 to 60 billion tons. Current investigations focus on the characterization of the coals in terms of stratigraphic occurrence, quality, and areal distribution. Coal-bearing outcrops were sampled and described, and selected geophysical logs from oil and gas wells in the region have been analyzed.

Surface exposures of the coal beds occur in a belt extending more than 50 miles from the White Hills eastward to the Kavik River. Sections were measured along the Sagavanirktok River near Sagwon, at two locations on the Shaviovik River, and at Juniper Creek. The coal-bearing outcrops consist primarily of interbedded sandstone, siltstone, shale (mudstone), carbonaceous shale and coal. Sandstones are dominantly fine to medium grained and ripple laminated to trough crossbedded; pebble lag occurs at the base of troughs. Shales are commonly interbedded with both siltstone and very fine grained, ripple-laminated sandstone, and locally the shales are bentonitic. Both shales and siltstones contain abundant coalified plant fragments. Siderite concretions occur throughout the coal-bearing section.

The coal beds in outcrops range in thickness from 2 to 12 feet, and many contain layers of coaly carbonaceous shale and bone (high-ash) coal interbedded with bright coal. Clay partings are abundant. Analyses of 16 coal samples from 11 coal beds indicate that the apparent rank of the coal ranges from lignite A to subbituminous B, and is most commonly subbituminous C. Average values for the ash and total sulfur are 7.5 percent and 0.3 percent respectively.

Subsurface data on the coal-bearing sequence are from oil and gas test wells within the Prudhoe Bay region. Interpretation of 10 geophysical logs from wells located along a 50-mile line between the Kuparuk and Kadleroshilik Rivers near the Arctic coast indicates that the coal-bearing sequence, defined here as the interval between the stratigraphically highest and lowest coal beds, ranges in thickness from 720 to 1,340 feet. Depth to the top of the sequence increases west to east from 2,800 feet to 5,400 feet. Coal bed thickness ranges from 2 to 25 feet, with cumulative coal thickness generally constituting 6–8 percent of the total thickness of the coal-bearing interval.

Results of these investigations will further delineate the extent of coal bed occurrence in Upper Cretaceous and Tertiary rocks, and better define the coal resource potential within this large area of Alaska's North Slope.

Sequential, Time-Slice Paleogeography of Northwest Borneo, Southeast Asia, as a Basis for the Delineation of Oil and Gas Plays

Keith Robinson

The island of Borneo appears to have formed as a result of the southward migration, rotation, collision, and accretion of a series of microcontinental blocks. These blocks were possibly rifted from the southern margin of the Asian continent and then impeded in their southerly migration by the Australia-India plate in their present-day location. The blocks were probably transported along a complex series of right-lateral transcurrent wrench faults, and were associated with, or directly related to periods of subduction and sea-floor spreading in both the South China Sea and the Makassar Strait. Interaction between the plates resulted in the development of major sedimentary depocenters and stable shelf areas.

The present "microcontinental"-margin Tertiary basins in Borneo are all fault controlled. These basins formed parallel to the coastline, controlled by major northwest-trending transcurrent wrench faults. Zones of weakness in the pre-Tertiary basement, parallel to the coastline, caused the continental margin to collapse in response to regional subduction or pull-apart stresses and sedimentary loading. The collapse resulted in the development of a series of normal faults which drop the basement successively seaward, characteristic of a continental passive margin.

Significant hydrocarbon discoveries in Brunei and the Malaysian states of Sarawak and Sabah, of northwest Borneo, are confined to coastal and offshore Tertiary sedimentary basins. The complexity of both the depositional history and structural development gives rise to numerous exploration play prospects. Controlling factors in play development are the environment of deposition, the type of sediment deposited in each play area, and the structural configuration, or physical geometry, of the feature receiving the sediment. Structural and sedimentary features controlling exploration plays in northwest Borneo include fault-bounded horst, graben, and half-graben structures; gently folded to highly faulted and asymmetrical anticlines; synsedimentary growth-fault and roll-over features; structurally controlled deep-marine turbidites; carbonate platforms; pinnacle reef complexes; and delta systems.

A major marine regression in northwest Borneo occurred during Paleocene through middle Eocene time, in response to intense cordilleran uplift of a young mountain range near the present Malaysian-Indonesian border. Late Eocene to early Miocene was a time of widespread marine transgression. An active subduction zone, emergent mountain ranges, marine trenches, rapidly-filled marginal basins, and carbonate platforms developed during this period. In contrast, middle Miocene through early Pliocene was a time of general regression, accompanied by repeated periods of intense tectonism. Late Pliocene to the present has been characterized by cyclical periods of marine regression and transgression. The post lower Miocene period to the present has been marked by the development of large delta systems, carbonate platforms, pinnacle reefs and shallow marine clastic wedges.

Studies of the tectonic evolution of northwest Borneo and an interpretation of probable associated paleoenvironmental conditions that prevailed make it possible to reconstruct a scenario of conditions that existed at any one time during the Cenozoic era. A sequential geologic reconstruction of these conditions, through time, leads to the delineation of new potential plays and geographic areas for hydrocarbon discovery. Current oil- and gas-producing plays in northwest Borneo are predominantly confined to deltaic systems and pinnacle reef growths.

Diagenesis of Sandstones in the Permian Upper Part of the Minnelusa Formation, West Mellott Field, Powder River Basin, Wyoming

C.J. Schenk, R.M. Pollastro, and J.W. Schmoker

Dolomite-anhydrite-sandstone cycles of the Permian upper part of the Minnelusa Formation, Wyoming, record multiple progradations of marine, siliciclastic sabkha, and eolian sediments. Heterogeneity in the sandstones, studied in five cores from present-day depths between 7,100 and 7,325 feet, is partly the result of diagenetic alterations. The earliest alteration was the formation of clay coatings on the detrital grains, particularly in siliciclastic sabkha and related eolian sandstones. Quartz cement formed syntaxial overgrowths, particularly in the sabkha sandstones. Carbonate clasts in the sandstones were pervasively dolomitized, as were the adjacent carbonate beds, possibly by seepage-reflux of brines that formed during the evaporitic stage of the next sedimentary cycle. The sandstones were then partially cemented with poikilitic anhydrite (or gypsum). Clay coatings and cementation by anhydrite did not completely prevent a progressive loss of intergranular volume by pressure solution with burial.

The illitization of early clay coatings was also a progressive process with burial. The present-day clay mineral assemblage in the sandstones consists predominantly of illite and ordered illite/smectite. The authigenic overgrowth and intergrowth morphology of the clay coatings suggest that they were probably more smectitic in composition when introduced into the sands, and were progressively converted to their present illitic composition during burial.

Late-stage dissolution of anhydrite produced irregularly distributed secondary sandstone porosity; dissolution was most complete in the upper parts of eolian-dune and reworked-eolian sandstones, resulting in excellent reservoir properties. Late-stage dissolution of potassium feldspars also occurred, as evidenced by the lack of compaction of the partially dissolved grains. Small rhombs of authigenic dolomite grew along most of the secondary pores and partially replaced the remaining anhydrite. Laths of authigenic illite formed on the dolomite, although this illite phase is rare. Quartz cement formed subsequent to the dolomite, in some cases engulfing the dolomite rhombs in syntaxial overgrowths. Hydrocarbons then migrated into and occupied the secondary porosity of the upper parts of the eolian-dune sandstones and reworked-eolian sandstones. Pyrite is present as an authigenic phase that automorphically replaced anhydrite and quartz, but its position in the paragenetic sequence was difficult to determine.

Sedimentology of the Permian Upper Part of the Minnelusa Formation near Beulah, Wyoming— Analog for Subsurface Facies in the Powder River Basin

C.J. Schenk, J.W. Schmoker, J.E. Fox, and M.W. Lee

Sandstones in the upper part of the Minnelusa Formation host an important group of hydrocarbon reservoirs. Exploration for additional reservoirs is difficult because of a complex intercalation of the sandstones with other lithologies. Outcrops near Beulah, Wyoming, provide a three-dimensional sedimentologic perspective of this complexity, and constitute a unique opportunity to refine sedimentologic interpretations based solely on subsurface data in the main area of Minnelusa production.

The upper part of the Minnelusa near Beulah consists of dolomite, gypsum (anhydrite in the subsurface), and sandstone units deposited in transgressive-regressive cycles. Each dolomite records a marine transgression across relict eolian-dune topography of the previous cycle. The dolomites contain a sparse fauna of brachiopods, crinoids, and pelecypods, and were probably originally micritic, indicating deposition in a low-energy marine environment of normal salinity. Gypsum (anhydrite) above the dolomite records restriction of the water body as sea level began to fall; the gypsum onlapped and then covered the eolian-dune sandstones. The fine lamination, thick beds, and onlapping relationship to the eolian dunes indicate a low-energy subaqueous origin, rather than a sabkha origin, for the gypsum.

Low-energy marine, sabkha, and eolian-dune sandstones record continued regression. Marine sandstones are uncommon in outcrop, and consist of bioturbated to irregularly bedded sandstone with thin clay interbeds, suggestive of low-energy conditions. The sabkha sandstones consist of wavy-bedded to irregular strata formed by algal growth and trapping of sediment and possibly by salt-ridge formation, indicating a low-energy intertidal to supratidal environment of deposition. The eolian-dune sandstones record the repeated southward movement of a sand sea across the sabkha sediments. The extent and distribution of eolian dunes differed from cycle to cycle. Where eolian sandstones were not preserved, marine and sabkha sandstones are directly overlain by marine dolomites of the next cycle.

The eolian dunes were partially reworked during the next cycle's transgression. Eolian ripple strata and high-angle sandflow cross-strata of the dune sandstones grade laterally into contorted and massive-bedded sandstone. In some areas, water-saturated eolian sand slumped from the dune to form an apron of reworked sand that was subsequently bioturbated. These reworked sands indicate that the eolian dunes were not cemented prior to the next transgression.

Dependence of Sandstone Porosity upon Thermal Maturity—An Approach to Prediction and Interbasinal Comparison of Porosity

James W. Schmoker and Donald L. Gautier

Porosity estimation of deeply buried and sparsely drilled reservoir rocks is fundamental to hydrocarbon exploration. The loss of porosity by burial diagenesis is hypothesized here to be, in many sandstone reservoirs, principally the result of thermal stress. Data show that porosity loss can be described by a power function of the form:

$$\phi = a(M)^b,$$

where ϕ is porosity and M is thermal maturity expressed as vitrinite reflectance, Lopatin's time-temperature index (TTI), or another measure of thermal maturation. Basing porosity-decline curves on levels of thermal maturation rather than on depth allows direct comparison of sandstones of different ages, compositions, and tectonic histories (fig. 1).

The petrologic coefficient a in the above equation incorporates the net effect upon porosity of all depositional and diagenetic factors, and thus a can vary significantly. For example, fine-grained sandstones and low values of a are commonly associated, whereas extensive secondary porosity is characterized by a high value of a.

The exponent b reflects rate-limiting steps in principal mechanisms of porosity loss. In concept, rates of porosity loss with thermal maturation could vary significantly, but empirical data show that the magnitude of b remains within a relatively narrow range. The variability of sedimentary and diagenetic processes in the natural system appears to be sufficiently limited for porosity prediction based on thermal maturation to be feasible and useful.

Offshore Resource Geology of the Western United States—A New Continental Margins Volume

David W. Scholl, Arthur Grantz, and John G. Vedder

The geologic framework and resource potential (hydrocarbon and mineral) of offshore Western North America, from the Arctic Ocean to Baja California, including the United States Exclusive Economic Zone (EEZ) are described in a new continental margins volume. The volume contains the results of investigations through the last 20 years by USGS and non-USGS scientists. Some papers are based primarily on newly collected data, and others incorporate previously published observations largely recast in light of newer data and interpretations, and evolving understanding of the structural and stratigraphic history of the continental margin.

The volume is organized into three sections. The first section presents the framework geology and resource potential of tectonically and geographically defined sectors of continental and island-arc margins and their bordering shelves. The second section groups chapters describing the ocean basins bordering these margins. Specific hydrocarbon and mineral resources are treated topically in the third section. The regionally oriented chapters are arranged in geographic order, beginning with the Beaufort Sea in the north and progressing southward to the Pacific offshore of Baja California. The topical chapters summarize, or provide broad exploration perspectives for, a variety of potential

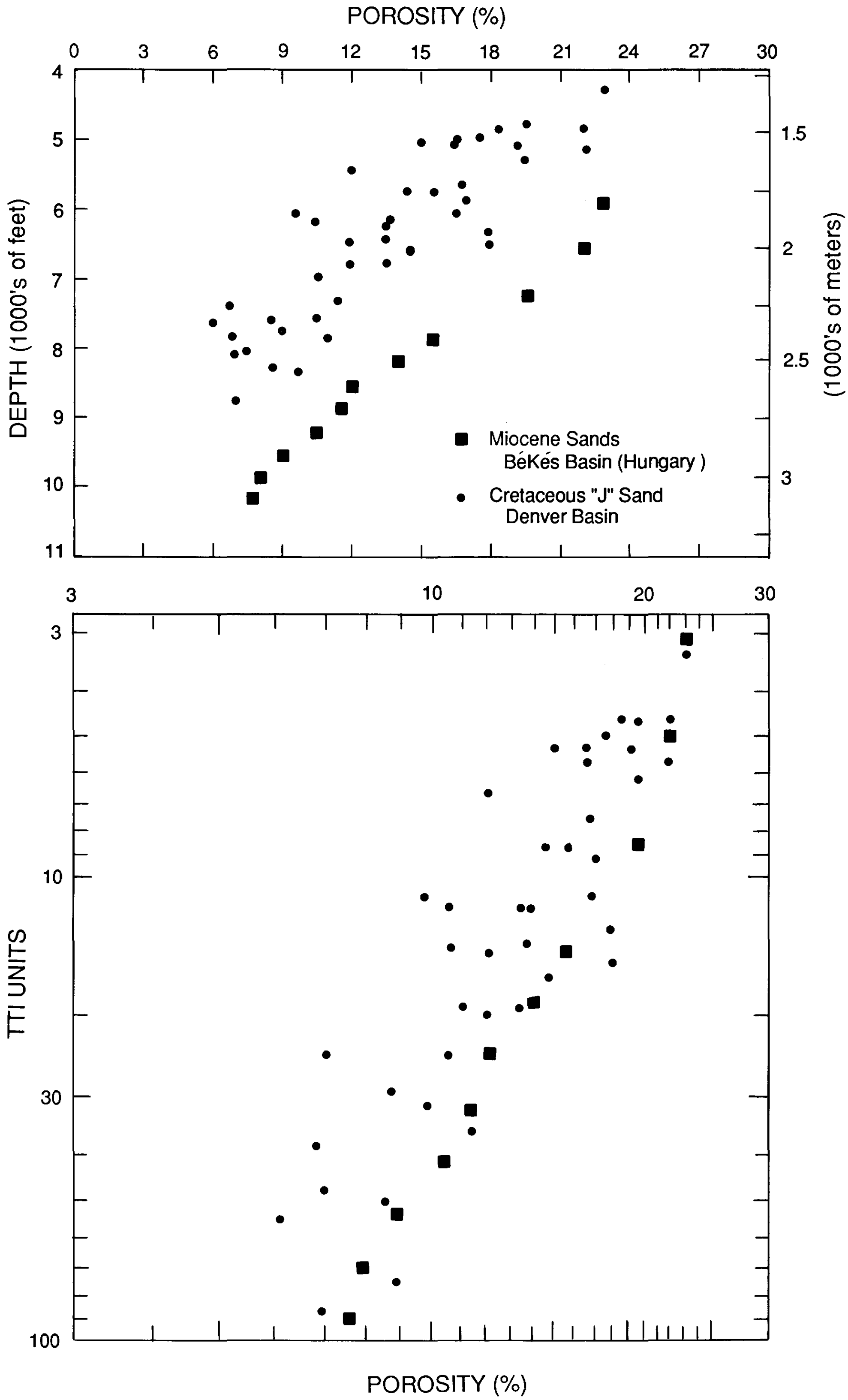

Figure 1. Comparison of sandstone porosities from a stable, uplifted foreland basin (Denver basin) and a young, hot, extensional basin (Békés basin, Hungary). Use of thermal maturity (TTI) rather than depth as a porosity-prediction parameter permits direct comparison of sandstones from diverse tectonic settings. In the lower panel, effects of age, thermal gradient, and burial history are incorporated into TTI, and remaining porosity differences between the two sandstones reflect petrologic dissimilarities.

offshore resource commodities. Part of the USGS mission is to search out and determine the availability of resources that may presently be subeconomic, but which the Nation may rely on in the future; many chapters in this volume address that mission.

Pakistan—A Coal-Geologists' Paradigm

S.P. Schweinfurth, M.J. Bergin, W.O. Fredericksen, R.T. Hildebrand, E.R. Landis, W.F. Outerbridge, J.F. SanFilipo, F.O. Simon, P.D. Warwick, and C. Wnuk

Coals of Pakistan occur in a varied and fascinating array of settings in terms of origin, preservation, quality, and rank development. Coals of Paleocene and Eocene age occur in relatively flat lying, unexposed subsurface deposits as well as in highly folded and thrust-faulted terrains. Coals of Permian age (Gondwanian) crop out locally in Punjab Province—an area of complex structure. Geophysical surveys suggest that additional Permian coals may occur in the subsurface, and one record exists of deep Permian coal in an oil and gas test well.

Although little is known of the Permian coals, enough is known of the Tertiary coals to stimulate great interest in their continued study—not just as a commodity (which is the principal interest of Pakistan) but from a coal-science point of view. Tertiary coals apparently formed on the margins of the Indo-Pakistan continental plate as it was "sailing" northward to "dock" with the Eurasian plate. This inference helps to set the regional paleogeography for the origin of these coals and aids in initial interpretations of their sedimentologic patterns, but the details of each deposit remain a mystery and await unraveling by enterprising coal geologists. After the collisions of the continental plates, the coal deposits were subjected to various amounts of structural modification, from simple to severe.

Although the existence of coal deposits in Pakistan has been known for many years and gross estimates of coal resources have been reported by the Geological Survey of Pakistan (GSP), relatively few details of their geology and resource potential appear in the literature. Intermittently between 1955 and 1966, USGS personnel conducted coal-resource assessment work in Pakistan under the aegis of the U.S. Agency for International Development (USAID). In 1985, USAID invited the USGS to return to Pakistan, to design and monitor a coal-resource exploration and assessment program (Coal REAP) in southern Sind Province. The objective of this ongoing coal exploration program is to demonstrate sufficient in-place coal reserves to support the development and maintenance of coal-fired electric power generation in Pakistan. The task of carrying out the assessment fell principally to USGS coal scientists, working closely with GSP counterparts as coordinators, planners, and teachers. The GSP geologists provide field support and knowledge of the terrain. The coal resource assessment work is facilitated by drilling wherever appropriate, and data from the drill and geophysical logs provide the essential third dimension to coal-deposit modeling work.

To 1987, this coal exploration program in Pakistan has resulted in the discovery of additional coal resources in southern Sind, and USAID has invited the USGS to expand Coal REAP studies into two additional provinces, Punjab and Baluchistan. If the coal exploration and assessment program continues to progress successfully, this work may continue for as long as 5 more years.

Abnormally High- and Low-Pressured Oil and Gas Reservoirs—Examples from Rocky Mountain Region

Charles W. Spencer

Oil and gas reservoirs with abnormally high or abnormally low pressures are present in many basins in the United States and worldwide. The above-normal (overpressured) reservoirs are generally deep (>10,000 ft), are gas bearing, and in onshore basins usually occur in low-permeability (tight) reservoir rock sequences. Reservoirs with below-normal pressures are mostly shallow (<10,000 ft), usually contain gas or oil and gas, and occur in both tight and permeable (conventional) reservoirs.

Overpressuring in deep, *rapidly* deposited strata is commonly caused by dewatering of shales and siltstones; some contribution of pressure also results from clay mineral transformations and (or) hydrocarbon generation (usually gas). Examples in the United States can be found in the Gulf Coast area. Hydrocarbon generation is believed to be the primary cause of overpressuring in oil- and gas-producing reservoirs that were *slowly* buried. Slow deposition generally allows sufficient time for the shales and siltstones to expel water and to compact prior to attaining subsurface temperatures sufficiently high for oil and gas generation. This type of overpressuring is common in many Rocky Mountain basins, where it occurs mostly in rock sequences of Cretaceous age, but overpressured oil reservoirs also occur in very kerogen-rich rocks of Tertiary and Paleozoic age.

Abnormally low reservoir pressures seem to be caused mostly by gas diffusion and gas shrinkage in reservoirs that have been uplifted or otherwise cooled.

Recharge of these low-pressure reservoirs by meteoric water does not occur rapidly enough to repressure the reservoirs to a normal hydrostatic pressure. Shallow reservoirs with normal to slightly above normal pressures occur in areas where the rocks have better hydraulic continuity to recharge areas. Examples of underpressuring can be found in gas-bearing sandstone and carbonate reservoirs in the Rockies that range in age from the late Paleozoic to Tertiary.

High pressures in the Rocky Mountain region are significant because the overpressured rock sequence is deep (hot) and has relatively rich source beds, the producing intervals are oil or gas saturated, and discrete hydrocarbon-water contacts are generally not present. Water production may occur (and it is usually not a constraint to production), but the low permeability of the reservoir rocks can be a problem. Although hydraulic fracturing is commonly used in well completions, natural fracturing seems to be necessary for good production rates and ultimate recovery. Classical hydrodynamic concepts are not applicable to overpressured intervals in the Rockies. The optimum depths for exploration are generally the upper 1,000–2,000 ft of the overpressured rock sequences. Improved prices and completion methods would be needed to make deep, overpressured wells more economic.

A Major Eocene Suture in the Southern Washington Cascades—Are Hydrocarbon Source Rocks Buried Beneath Volcanic Flows?

Dal Stanley, Bill Heran, and Carol Finn

Deep geophysical studies have been carried out in the western half of Washington and portions of western Oregon, relying primarily upon magnetotelluric (MT) soundings to locate undetected sedimentary rocks that could serve as hydrocarbon sources. These studies have been designed to locate any sedimentary basins or complexes lying beneath the extensive Tertiary and Quaternary volcanic flows and oceanic crustal rocks west of the Cascade Mountains in Oregon and Washington. Although hydrocarbon exploration has been relatively active in the Columbia Basin of eastern Washington, the only successful hydrocarbon production has been from the Mist Gas Field region west of Portland, Oregon. In the region west of the Cascades in Oregon and Washington, several distinct forearc basins have been explored, including the Astoria, Gray's Harbor, Chehalis, and Willamette Basins. All these basins contain 1–5 km of Eocene marine sediments with low maturation indices. The Mist Gas Field lies east of a saddle between the Astoria and Willamette Basins; geochemical analyses of the gases from the field imply a deeper origin for the gas than can be provided by sediments from the nearby basins.

Extensive MT surveys in Washington and Oregon have been interpreted to postulate the existence of very thick marine sediments in a proposed suture zone in the southern Washington Cascades. This hypothesis is based upon the occurrence of a mapped highly conductive body with resistivities of 1–5 ohm-m and thicknesses of 5–15 km. The conductive body dips to the east; it is bounded by accreted seamount complex and other oceanic crustal rocks on the west and resistive, possibly continental crust on the east. Four lithologies have been evaluated as possible causes of the high conductivity anomaly; in the preferred model for the feature, an early Eocene forearc basin containing 5–7 km of marine sediments was compressed and partially subducted during accretion of the extensive seamount complex that makes up the Coast Ranges of Oregon and Washington. Other geophysical and geological data support the preferred model.

The shallowest portions of the conductor correlate with outcrops of transitional marine units in the lower part of the Puget Group in the Carbon River anticline west of Mount Rainier. Tectonic reconstructions suggest that, whereas the upper part of the conductor may be composed of such Eocene marine sediments, part or most of the conductor could consist of Paleocene or older sediments.

Possible source and reservoir implications of this geophysical anomaly have been considered, and relations to nearby known basins, such as the Chehalis Basin, have been evaluated; important research for the future includes surface geochemical studies and completion of a deep reflection profile. This model is important not just for evaluation of hydrocarbon potential for the region: the suture zone between the accreted seamount complex and the proposed marine basin may control the location of a seismically active strike-slip zone that passes through Mount St. Helens and may thus provide a key constraint in the location of the volcano itself. The studies were supported by the Department of Energy, Morgantown Energy Technology Center.

Eocene Lava and Epigene Mineralization Alter Alaska's Thickest Known Coal Deposit

Gary D. Stricker and Ronald H. Affolter

Alaska's thickest known coal accumulated in the 4 square mile tectonic Boulder Creek basin in Death Valley, southeastern Seward Peninsula, Alaska. Bedrock in the area consists of Precambrian(?) and Paleozoic metamorphic rocks that were intruded in the Late Cretaceous by acid magmas resulting in the formation of alkalic monzonitic plutons. Post-intrusive faulting formed the Boulder Creek graben, which filled with sediments and organic debris. An 80-foot-thick Eocene basaltic lava flowed into a thick peat swamp, catastrophically ending organic accumulation. Subsequent epigenetic mineralization began after deposition of the host sediments and has continued to the present. The geochemical effects of lava and epigenetic mineralization in Death Valley make this coal deposit unique.

Exploratory core holes in the graben, drilled for uranium, contained three coal beds, with one bed exceeding 165 ft thick. Chemical analyses were determined on six vertical increments of the thick coal from two core holes, and vitrinite reflectance was determined on 20 random samples taken throughout this coal.

Mean random vitrinite reflectance values are 0.4 *Ro* percent at the base and 2.6 *Ro* percent at the top. Total sulfur content ranges from 0.38 to 1.5 percent with the highest value near the base of the bed. Ash content is variable from 2.3 to 6.8 percent. Significant enrichment in the contents of Cu, F, Hg, K, Li, Mg, Na, Ni, Pb, and Sr occurs within the top 35 ft of the coal bed. These elements were mobilized in the basalt by steam produced by the violent reaction of lava entering the wet peat swamp.

Uranium content of 37 ppm (whole coal) in the basal 30 ft of the coal represents an enrichment of 30 times the average for other United States coals. Uranium was derived from the nearby plutons and concentrated in the base of the coal during and after peat accumulation by epigenetic mineralization. The basalt may have acted as a barrier to these mineralizing fluids, thereby minimizing the enrichment of uranium at the top of the bed. Death Valley coal has the highest reported content of tungsten (360 ppm whole coal) for any United States coal. A linear correlation of 0.95 between uranium and tungsten suggests that the epigenetic mineralization phase which concentrated uranium also concentrated tungsten.

Apparent rank increases from subbituminous C near the coal's base to semianthracite at the top. This, coupled with high tungsten and uranium content, makes the Death Valley deposit different from other Alaskan and United States coals. Intense heat over a relatively short time interval and epigenetic mineralization are the major factors affecting rank and element distribution in this coal and warrant further investigation.

Overthrusting in the Northwestern San Juan Basin, New Mexico—A New Interpretation of the Hogback Monocline

David J. Taylor and A. Curtis Huffman, Jr.

The Hogback monocline is a prominent northeast-trending structure that bounds the northwestern edge of the San Juan Basin. Multichannel seismic reflection lines, shot at various angles to the monocline in the vicinity of Waterflow, New Mexico, reveal a series of complex faults at depth. The seismic data together with selected adjacent well data have allowed us to locate the major faults, identify the type of faulting involved, and determine the movement along the faults over time. Domal structures genetically related to the observed faulting are major hydrocarbon producers in this part of the San Juan Basin. (See sketch, fig. 1.)

Twelve-fold CDP seismic reflection lines and geophysical well logs provided the primary information input to this investigation. Six stratigraphic boundaries were identified from the well logs and were correlated with the seismic data through the use of synthetic seismograms. Interval velocity data used in converting the picked time horizons to depth were established from acoustic and resistivity logs from all sides of the major faults.

These data yield a pattern of intersecting northeast- and northwest-trending faults of probable Precambrian ancestry. These faults display a complex history of movement. For example:

1. Northwest-trending faults exhibit vertical components of movement from early Paleozoic through at least Triassic time.
2. High-angle reverse faulting and significant thrusting during the Laramide are evident on both northwest and northeast faults including northeast-, southeast-, and southwest-directed thrusting.

The observed fault pattern was most likely inherited from Precambrian orogenic movements. Thickness variations between northwest-trending blocks indicate vertical movement along a northwest-trending fault zone during the Paleozoic and early Mesozoic. During the Laramide, general east-west shortening resulted in right-reverse movement along the northeast-trending fault zone, left-reverse movement along the northwest-trending zone, and transpression in the area of intersection that produced concurrent overthrusting in several directions, forming the Hogback monocline and related hydrocarbon-rich domal structures.

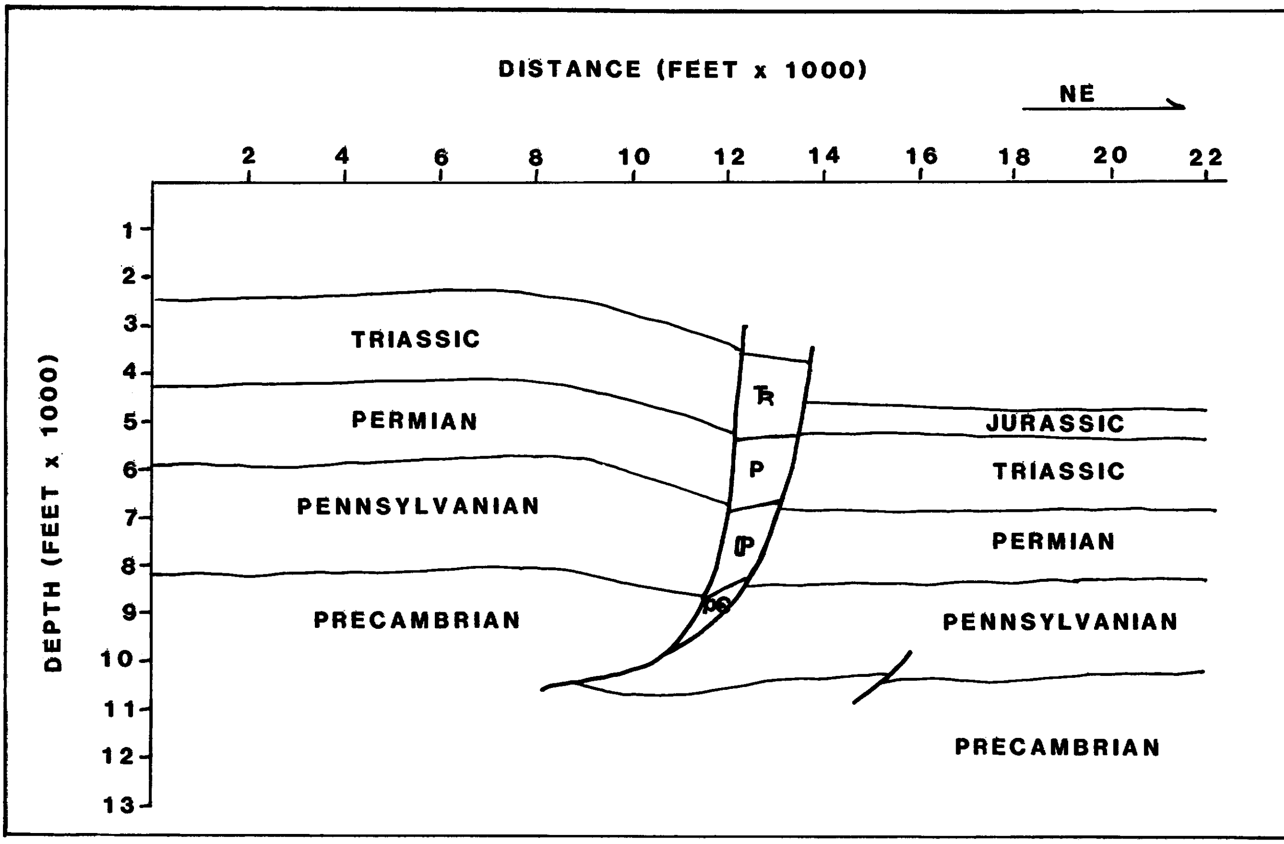

Figure 1. Depth-converted seismic data across Hogback monocline showing thrust faulting and related domal structure.

Tectonic History and Petroleum Potential of Eastern Washington and Oregon

Marilyn E. Tennyson and Judith Totman Parrish

Petroleum resource assessment in the Pacific Northwest east of the Coast Range is complicated by extensive Cenozoic volcanic cover. Analysis of tectonic history is one approach to characterizing potentially prospective sedimentary sequences and attempting to deduce their distribution beneath volcanic rocks. Evaluation of this region for the Federal Lands Assessment Program was based on integration of regional history with lithologic and stratigraphic data from outcrops and drill holes. Two sequences with some potential are an Upper Cretaceous marine section in Oregon and an Eocene fluvial sequence in central Washington and northern Oregon.

Allochthonous terranes in the Klamath and Blue Mountains of Oregon comprise Paleozoic and Mesozoic ophiolitic, subduction-complex, and arc rocks formed at southerly latitudes. Unconformably overlying Albian-Maastrichtian marine clastic rocks 4,000–8,000 ft thick (Ochoco, Mitchell, and Hornbrook sequences) demonstrate that the allochthonous terranes were in place by Albian time, then partially covered by detritus eroded from accretion-related uplifts. Eastern Washington lacks an analogous Upper Cretaceous post-accretion marine sequence.

The Eocene continental margin was characterized by oblique convergence between North America and the Kula plate. Calc-alkaline volcanism and right-lateral faulting took place east of newly accreted Coast Range basaltic basement. Crustal extension in Washington, British Columbia, and Idaho was associated with unroofing of crystalline rocks, which provided large volumes of arkosic detritus. The resulting sediments accumulated to more than 20,000 ft in strike-slip basins in central Washington and 0–2,000 ft in fluvial systems in Oregon, apparently outside fault-controlled basins. Cascade arc volcanism began in Oligocene time and has continued through the Neogene. In Miocene time, the Columbia River Basalt Group erupted from fissures in easternmost Washington and Oregon, flowed down west-sloping dissected topography, and lapped onto the Cascade arc. Episodic deformation accompanied volcanic activity.

In Oregon, gas—or less probably, oil—could have been generated from mostly Type III organic matter in the Cretaceous sequence or from organic-rich or coaly intervals in the Eocene fluvial sequence. Eocene arkosic sandstones have adequate reservoir characteristics, but Cretaceous sandstones do not. Widely scattered wells reveal marked lateral stratigraphic variation in the Cretaceous and Eocene sequences: both are widespread, but each is also locally absent, and thicknesses vary. In only a few localities are both Eocene and Cretaceous rocks present, but because Eocene fluvial sediments were probably deposited on a subcrop surface consisting of both accreted terranes and overlying Upper Cretaceous rocks, it seems possible that both sequences coexist beneath volcanic cover.

In central Washington, drilling has shown that the Eocene fluvial sequence continues beneath Miocene basalt and that it contains some gas. Lacustrine mudstone and coal, potential source rocks, are present in this section where it is exposed around the perimeter of the basalt. Lopatin modeling based on published vitrinite reflectance data suggests that burial by basalt in middle Miocene time caused maturation of the Eocene section. Porosity in samples from recent drill holes varies but is reported to be adequate (13–16 percent) in tested stratigraphic intervals. Quantities of gas and condensate tested in wells drilled so far are insufficient to offset the costs of drilling through basalt 5,000–11,000 ft thick.

Low-Temperature Formation of Illite—Implications for Clay Geothermometry and Hydrocarbon Generation

Christine E. Turner-Peterson, Neil S. Fishman, and Douglass E. Owen

Diagenetic illite/smectite in sedimentary rocks is used widely as a geothermometer in evaluating the thermal history of potential hydrocarbon-bearing sequences. The conversion of smectite to illite/smectite is generally thought to begin when temperatures reach 90 °C. Thus, the conversion is used as a geothermometer to determine if a sedimentary sequence has been buried to sufficient depths to have generated hydrocarbons. The conversion itself has also been linked to the generation and expulsion of hydrocarbons. Moreover, the conversion frees abundant fresh water, which can lead to abnormally high fluid pressures in fine-grained rocks; these fluid pressures are used throughout the petroleum industry as keys to hydrocarbon production.

Use of diagenetic illite/smectite as a geothermometer stems largely from analogies with the Tertiary section of the Gulf Coast, where the proportion of illite layers in illite/smectite clay increases with increasing burial depth. Recently, however, it is increasingly apparent that the Gulf Coast model cannot explain all occurrences of illite/smectite in sedimentary rocks and that pore-water chemistry may be more significant than temperature in certain cases. Pore-water chemistry has been acknowledged as an important constraint for this reaction because a source of potassium is required, but it has not generally been thought that pore-water chemistry alone can facilitate the conversion from smectite to illite/smectite in the absence of elevated temperatures. (Whether authigenic illite/smectite can precipitate directly from solution is unclear.)

Saline, alkaline lakes, because of their extreme pore-water chemistry and hydrogeochemical zonation, are an appropriate setting to evaluate the role of pore-water chemistry in the formation of clay minerals. Some workers have suggested that the pore-water chemistry of saline, alkaline lakes might be conducive to the formation of illite at low temperatures (< 90 °C). Saline, alkaline lake deposits in the Brushy Basin Member of the Jurassic Morrison Formation, Colorado Plateau, provided a natural laboratory to test this hypothesis.

In this study, analyses of clay separates from tuff beds reveal a pattern of increasing illite content in the illite/smectite (in stratigraphically equivalent intervals) toward the center of the lake. This trend in clay mineral composition coincides with the systematic basinward change from authigenic zeolites to feldspars, a change which reflects a steep hydrogeochemical gradient, with inferred salinities and alkalinities of the pore waters increasing toward the center of the lake. Randomly interstratified illite/smectite clay (80–100 percent smectite layers) occurs either as the predominant mineral or with clinoptilolite in the two outermost lake facies. In contrast, ordered illite/smectite (0–30 percent smectite layers) occurs in association with authigenic albite in the central lake facies. Mixed-layer illite/smectite of highly variable composition (20–80 percent smectite layers) occurs with analcime and authigenic potassium feldspar in the intervening lake facies. The absence of illite in the two outermost lake facies precludes a detrital origin for the illite in the more central facies.

The way in which composition of mixed-layer illite/smectite mimics the zonation of early authigenic aluminosilicates (zeolites and feldspars) across the lake strongly suggests a pore-water control on clay mineral composition. We therefore infer a low-temperature, near-surface origin for the illite in contrast to the high-temperature (> 90 °C), deep burial conditions required by the Gulf Coast model of illite formation. As a result, caution should be exercised when illite is used as a geothermometer to evaluate the thermal evolution of sedimentary sequences.

Submarine Canyons of the Florida Escarpment, Eastern Gulf of Mexico

D.C. Twichell and L.M. Parson[1]

GLORIA (Geologic LOng Range Inclined Asdic) sidescan sonar images correlated with Sea Beam bathymetric data show that the Florida Escarpment, a steep carbonate cliff off western Florida, is incised by two different types of canyons. North of lat 27° N., canyons are narrow and straight, are spaced 3–8 km apart, and are fed by dendritic tributaries. These canyons extend from near the top of the escarpment to its base; some have small fans extending from their mouths. South of lat 27° N., large, flat-floored, and steep-sided box canyons deeply incise the escarpment and the West Florida Slope above the escarpment. These canyons are as much as 10 km wide; they are spaced 10–25 km apart and have nearly vertical head walls. Slumps on the West Florida Slope mostly feed into the box canyons.

The morphological differences between these two groups of canyons suggest different canyon-forming processes and variations in the erosional mechanisms that have operated along the length of the escarpment. The morphology of the northern type of canyons and of the fans at their bases suggests formation by downslope transport, whereas the box canyons are similar in appearance to canyons on land that have been attributed to undercutting by ground-water sapping. Evidence of ground-water discharge along the base of the escarpment has been found in localized areas south of lat 27° N., suggesting that sapping could have contributed to the development of the box canyons.

Geology and Petroleum Resources of the Barents–Northern Kara Shelf, U.S.S.R. and Norway

Gregory Ulmishek

The Barents–northern Kara shelf, one of the largest continental shelves in the world (2,450,000 km^2), is still in the earliest stage of exploration for oil and gas. Small-scale gravity and magnetic surveys provide the only data on the geology of large central areas of the shelf. Some seismic surveys and wildcat drilling have been conducted mainly along the western and southern margins. Geologic interpretation is based on these data, as well as on extrapolation of the stratigraphy and tectonics known onshore and on islands.

The pre-Late Devonian geology of the shelf is most uncertain. It appears that large transcurrent movements of continental blocks took place during and after the Caledonian orogeny. However, the common view that the shelf's basement is of Caledonian age is probably incorrect, and large areas may have a thick, undeformed lower Paleozoic section.

The Upper Devonian through Permian section is composed mainly of carbonate facies. The development of reefal buildups and associated black-shale facies may be predicted in a system of Paleozoic troughs stretching along the Norwegian shore and Kola Peninsula. Permian molasses derived from the Uralian Hercynides are not expected to extend far offshore.

The geology of a very thick (possibly 6–8 km) Triassic sequence is a key to evaluation of the region's petroleum potential. Correlation of Triassic rocks exposed and drilled on the shelf margins indicates the existence of a large sedimentary paleobasin covered by deep-water, black-shale facies of Middle Triassic age. This facies is presently known only on eastern Svalbard Archipelago, Norway; it is an excellent oil-source rock that is probably mature to overmature over most of the shelf.

Another potential source-rock interval is present at the top of the Upper Jurassic section. Black organic-rich shales here are the stratigraphic and facies analog of the oil-source Kimmeridgian shale of the North Sea and the Bazhenov shale of West Siberia. On the Barents shelf, however, these shales are probably immature, except in a few local depressions.

The present-day regional structural framework of the Barents shelf consists of deep basins along southern and eastern margins, and a generally uplifted area on the west and north. The most important basins are the Finnmark trough of mainly late Paleozoic age, and the South Barents and North Novaya Zemlya depressions, which are filled with very thick Upper Permian-Triassic clastics. These basins have the most interesting exploration potential. Other exploration targets are the late Mesozoic Tromso-Bjornoya rift in the southwestern part of the shelf and the offshore continuation of the Paleozoic Timan-Pechora basin on the southeast.

Several gas fields with total reserves of 5 to 10 trillion cubic feet and one noncommercial but geologically significant oil field have been discovered in the Norwegian part of the shelf. An important oil and gas-condensate field is being developed on the U.S.S.R.'s Kolguyev Island.

Geologic interpretation indicates high hydrocarbon potential for the Barents–northern Kara shelf, but also implies a significantly gas-prone character of the region. This emphasis on gas does not imply that rich oil plays

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cannot be found, but such plays will probably not be abundant. Development of gas fields in this remote polar region will not be economic for a long time; therefore, the main goal of future exploration will be to determine the combination of geologic factors that favor formation of oil versus gas accumulations.

Stratigraphy and Facies Analysis of Tertiary Units, Western Medicine Lodge Basin, Montana

Jean N. Weaver

Medicine Lodge Basin, in southwestern Montana, is an intermontane basin bordered on the south and west by the Bitterroot Range and on the east and north by the Tendoy and Pioneer Mountains. Basin deposits consist of as much as 9,900 ft of Eocene(?) to Miocene volcanic and sedimentary rock units. This study focused on the Oligocene(?) to lower Miocene(?) part of the sedimentary sequence. Stratigraphic and facies analyses of these Tertiary rocks resulted in recognition of three stratigraphic-facies units: a conglomeratic facies, which interfingers to the south with a coal-bearing facies, and an overlying platy shale facies.

The conglomeratic facies (up to 1,350 ft thick) is framework supported in the northern portion of the study area and matrix supported in the southern part. The principal internal structure of this unit is a series of en echelon conglomerate deposits, each one averaging 5 ft in length and 2 ft in thickness. Tertiary volcanic rocks and Precambrian quartzites make up the majority of the clasts, which are subangular to rounded, varying in size from pebbles to cobbles, some 8 in. in diameter. Crude pebble imbrication is visible. Towards the middle of the facies, conglomerate deposits are overlain by medium-grained 2–5 ft thick sandstone bodies, many of which are trough crossbedded. Conglomerate clasts are found at the base of these sandstone bodies.

Medicine Lodge Peak as viewed from Keystone Gulch, Medicine Lodge Basin, Montana.

The coal-bearing facies consists of alternating beds of sandstone, siltstone, shale, carbonaceous shale, and coal. The sandstone bodies (up to 6 ft thick), some with erosional bases, are fine to medium grained and display either trough crossbeds or ripple marks over conglomeratic lag deposits. Occasional plant fragments or root marks are present. Light-yellow siltstones, often plant rich, are found interbedded with medium-gray mudstones and shales (up to 5 ft thick). The less resistant shale units grade into either the overlying or underlying carbonaceous shale or coal beds. Carbonaceous shale beds (averaging 0.5 ft in thickness) are dark brown; many weather out as resistant ledges. Carbonaceous shale beds are also found as lenticular stringers within the coal beds, displaying gradational upper and lower contacts. Coal beds, lenticular in nature, can attain 5 ft in thickness.

The platy shale facies consists of tuffaceous, fissile brown shale that tends to weather white in resistant ledges. Fish, ostracodes, and plant fossils of middle Oligocene age are present throughout the facies. Limestone stringers are associated with this facies.

The conglomeratic and coal-bearing facies show a lateral change from the northern part of the study area down towards the south. The conglomeratic facies, which represents a very coarse clastic wedge, splits and interfingers with the coal-bearing facies to the south. The conglomeratic deposits and associated sandstone bodies represent deposition in a high-energy fluvial system. However, the sandstones are interpreted to be deposits of a low-energy fluvial system. The coal-bearing facies represent deposition in a fine-grained fluvial system. Associated with this latter system is a poorly drained floodplain in which coal and carbonaceous shale beds were deposited in detritus-free swamps. The overlying platy shale facies represents a freshwater lake. This shale facies, laterally extensive in the northern portion of the study area, is also present as thin units in the coal-bearing deposits in the south.

Detailed studies of these Tertiary deposits provide facies patterns of deposition of coal beds in Medicine Lodge Basin. Understanding their environments of deposition may assist in understanding coal accumulation in other Tertiary intermontane basins in southwestern Montana and northeastern Idaho.

Indigenous Sources of Fossil Fuels, Sahel Region of North Africa

Jean N. Weaver, Marion J. Bergin, Michael E. Brownfield, and Edwin R. Landis

The Sahel region, in north-central Africa, is located between the Tropic of Cancer and the Equator. Mauritania, Senegal, Mali, Burkina, Niger, Togo, Benin, Nigeria, Chad, Cameroon, Central African Republic, Sudan, Ethiopia, Rwanda, Burundi, and Tanzania are all within or adjacent to the Sahel region.

Occurrences of coal and (or) peat have been reported in all the Sahel countries except Burkina, Togo, Chad, and Uganda. Even in these latter countries, coal or peat deposits may exist, because neighboring countries contain coal-bearing rocks. Senegal, Niger, and Nigeria are the only countries in which coal or peat is actively mined. Coal is being used to generate electrical power as well as to supply some domestic heat and fuel; peat can be used as a fuel source, and has been used already in agriculture as a soil amendment. The primary domestic fuel source for these countries is wood charcoal; deforestation, overgrazing, nomadic cultural changes, and climatic changes, all linked to extended drought and desertification, have contributed to a severe wood charcoal shortage. This shortage suggests a real need to identify and develop indigenous fossil fuels in the Sahel countries. A concentrated study of the coal (lignite and higher rank) and peat occurrences within this region could identify a much needed alternative fuel source for the countries' economies.

Potential coal resource areas have been defined, using topographic and geologic parameters. Ten sedimentary basins have been identified from the literature: (1) Somali Basin, (2) Plateau and rift belt, (3) Sudan Trough, (4) Chari Basin, (5) Chad Basin, (6) Niger Basin, (7) Benue Trough, (8) Taoudeni Basin, (9) Senegal Basin, and (10) Gao Trough. Exposed Precambrian basement rocks surround most of these basins. From our preliminary studies, the potential for finding economic coal and (or) peat deposits within these basins appears to be high.

The economic and agricultural sectors of the Sahel region countries could greatly benefit from the development of indigenous fossil fuels. Use of fossil fuels may decrease or even halt the rate of desertification. Locating coal and peat deposits and evaluating their uses would help the countries' economic development, allowing them to become more self sufficient and less dependent on foreign energy resources.

Paleobotanical Composition of Some Pennsylvanian Coal Beds from the Central Appalachian Basin as an Indication of Paleoclimate

Richard B. Winston and Ronald W. Stanton

The abundances of peat-forming plant groups were quantified in a study of polished and etched blocks of coal, to help interpret climate changes during the Pennsylvanian Period in the central Appalachian basin. Floras were identified in 18 columnar samples from 13 coal beds that range stratigraphically from the Pocahontas No. 2 to the Pittsburgh.

Lycopods are most abundant (54–70 percent of botanical content) in the coal beds of the Pocahontas and New River Formations (Lower Pennsylvanian) and less common (42–46 percent) in the Upper Banner through Eagle coal beds of the lower part of the Kanawha Formation (Middle Pennsylvanian). Lycopods again reach high abundance (55 percent) in the Campbell Creek coal bed (Kanawha Formation) and then gradually decrease (35–55 percent) through the rest of the coal beds in the Kanawha Formation and Charleston Sandstone (Middle Pennsylvanian). Coal beds in the Conemaugh Formation were not investigated, but lycopods reached their lowest abundance (11 percent of botanical content) in the Pittsburgh coal bed of the Monongahela Formation (Upper Pennsylvanian). Pteridosperms, the other statistically important constituent, increase in abundance only in places where the beds are split by partings or where the beds thin.

Lycopods are interpreted to have been most abundant under the wettest conditions; their abundance has been used by previous workers as an index of relative "wetness" at least during the Lower and Middle Pennsylvanian. Our study indicates that the climate was wettest during the Early Pennsylvanian and became less wet during the early part of the Middle Pennsylvanian. Then, the climate abruptly became wetter in the middle of the Middle Pennsylvanian Series followed by gradual drying throughout the remainder of the Middle Pennsylvanian. The lycopods, which had formed much of the peat in the Lower and Middle Pennsylvanian, were becoming extinct during the Late Pennsylvanian; their ecological niche was being occupied by other groups, primarily ferns. Therefore, the abundance of lycopods cannot be used to compare the relative wetness during the formation of the Pittsburgh peat to the wetness of the Early and Middle Pennsylvanian.

Another explanation for the decrease in lycopod abundance through time—besides relative wetness—is that other plants were evolving greater tolerance for the environmental conditions of the swamps. Such an explanation would apply only to the gradual decrease in lycopods in the upper part of the Kanawha Formation through the top of the Charleston Sandstone. However, pteridosperms and ferns had already reached levels of abundance in the lower part of the Kanawha Formation as great as those found at the top of the Charleston Sandstone—so evolution probably does not explain these results.

In the abundance profiles of the columnar bed samples, two common patterns of lycopods abundance were observed: (1) lycopods decreasing in abundance toward the top of the coal bed, and (2) no correlation between position in the coal bed and lycopod abundance. The first pattern was found primarily in beds in the New River and the lower part of the Kanawha Formation, whereas the second pattern occurs throughout the section. Other less common patterns show pteridosperms increasing upsection within coals beds of the Lower Pennsylvanian and the lower and upper part of the Middle Pennsylvanian. The two major patterns of peat formation may also indicate differences of climate of the central Appalachian basin during the Pennsylvanian.

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