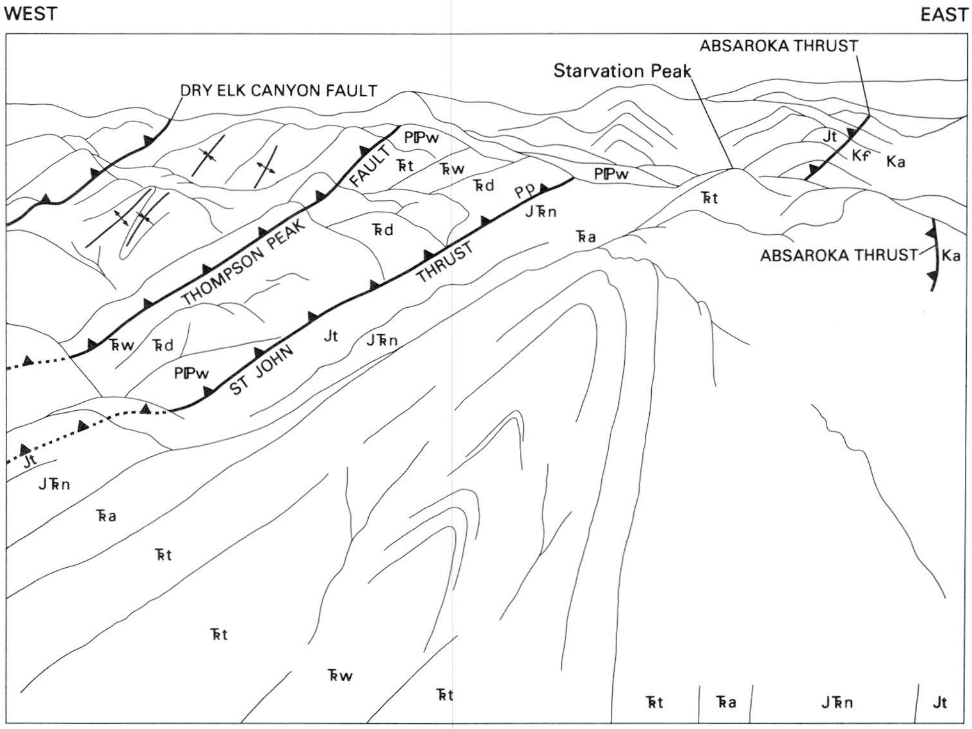
USGS Research on Energy Resources—1986 Program and Abstracts

V. E. McKelvey Forum on Mineral and Energy Resources

U.S. GEOLOGICAL SURVEY CIRCULAR 974



Cover.—Oblique aerial photographic view within Snake River Range northwestward toward Starvation Peak, Teton County, Wyoming, showing asymmetrical anticline in the Absaroka thrust sheet. Shape of fold and its structural setting are similar to those in the Ryckman Creek, Clear Creek, and Painter Reservoir fields producing oil and gas in southwesternmost Wyoming. Original color slide by S. S. Oriel, 1981.

Sketch of geology in the area: core of Starvation Peak anticline consists of lower Mesozoic Woodside Red Beds (Ꞧw), flanked by Thaynes Limestone (Ꞧt), Ankareh Red Beds, (Ꞧa), Nugget Sandstone (JꞦn) and Twin Creek Limestone (Jt). Twin Creek Limestone on east flank of anticline has been thrust northeast over Cretaceous Frontier (Kf) and Aspen (Ka) Formations along Absaroka thrust fault. Twin Creek on west flank of anticline is overridden by eastward-thrust Pennsylvanian quartzites of the Wells Formation (PIPw) and the Permian Phosphoria Formation (Pp) at base of St. John thrust sheet. Farther west, Triassic units (Ꞧd, Dinwoody Formation) in upper part of St. John sheet are overridden by Pennsylvanian Wells quartzite along base of Thompson Peak thrust sheet; tightly folded strata of this sheet are in turn overridden by rocks above Dry Elk Canyon fault. Sketch by A. L. Isom from geology by S. S. Oriel and others.

USGS Research on Energy Resources—1986 Program and Abstracts

Edited by L. M. H. Carter

V. E. McKelvey Forum on Mineral and Energy Resources

U.S. GEOLOGICAL SURVEY CIRCULAR 974

Department of the Interior

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U.S. Geological Survey

Dallas L. Peck, *Director*

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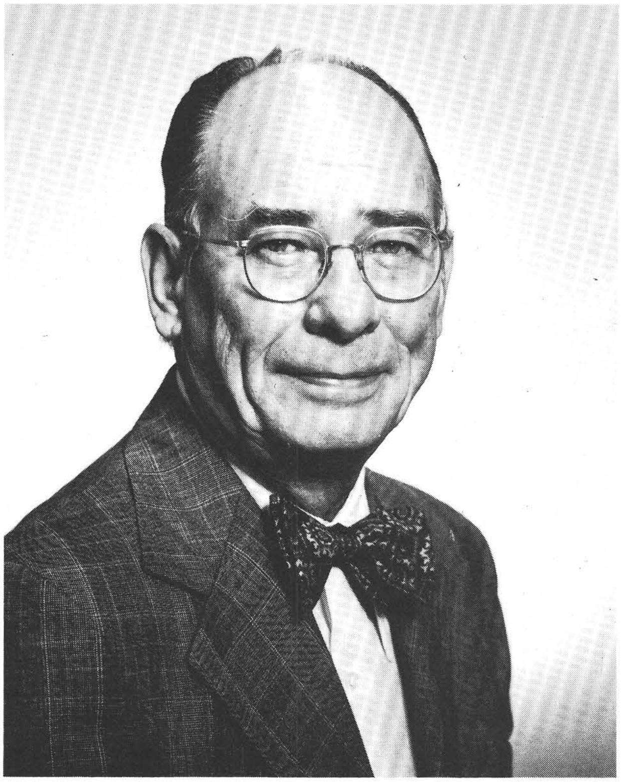
1986



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

FOREWORD

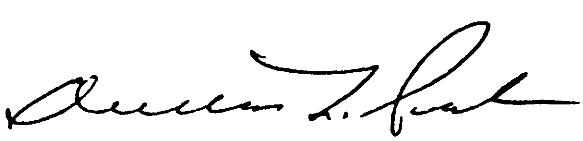
Dallas L. Peck, Director, U.S. Geological Survey

The extended abstracts in this volume are summaries of the papers presented orally and as posters in the second V. E. McKelvey Forum on Mineral and Energy Resources, entitled "USGS Research on Energy Resources—1986." The Forum has been established to improve communication between the USGS and the earth science community by presenting the results of current USGS research on nonrenewable resources in a timely fashion and by providing an opportunity for individuals from other organizations to meet informally with USGS scientists and managers. It is our hope that the McKelvey Forum will help to make USGS programs more responsive to the needs of the earth science community, particularly the mining and petroleum industries, and will foster closer cooperation between organizations and individuals.

The Forum was named after former Director Vincent E. McKelvey in recognition of his lifelong contributions to research, development, and administration in mineral and energy resources, as a scientist, as Chief Geologist, and as Director of the U.S. Geological Survey. The Forum will be an annual event, and its subject matter will alternate between mineral and energy resources. We expect that the format will change somewhat from year to year as various approaches are tried, but its primary purpose will remain the same: to encourage direct communication between USGS scientists and the representatives of other earth-science related organizations.

Energy programs of the USGS include oil and gas, coal, geothermal, uranium-thorium, and oil shale; work in these programs spans the national domain, including surveys of the offshore Exclusive Economic Zone. The topics selected for presentation at this McKelvey Forum represent an overview of the scientific breadth of USGS research on energy resources. They include aspects of petroleum occurrence in Eastern United States rift basins, the origin of magnetic anomalies over oil fields, accreted terranes and energy-resource implications, coal quality, geothermal energy sources, integrated geology and chemistry in uranium-deposit studies, and interpretations of sea-floor geology seen in reconnaissance-scale sidescan-sonar mosaics of the Gulf of Mexico and west coast Exclusive Economic Zone. Data are presented that are being used in building models of geothermal energy settings, basin histories, and the occurrence of energy resources. In addition to the technical sessions presenting the results of USGS research, each congressionally mandated USGS Mineral Resource Program has a display outlining plans and progress.

We are all excited about this continuing opportunity to disseminate and discuss our research with our colleagues in industry and academia, and we welcome your suggestions on improving this series of Forums.



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

Wednesday, February 5, 1986

8:15 a.m. —Session I (Grand Ballroom, Regency Hotel)

Terry W. Offield and Robert M. Hamilton, presiding

Opening remarks *Robert M. Hamilton*

An approach to integrated sedimentary basin analysis *Arthur Green*, keynote speaker

Terranes, resources, and the geodynamics of continental growth *David G. Howell and David L. Jones*

Paleoceanographic and tectonic influences on the deposition of the Monterey Formation of California *John A. Barron*

10:10 a.m. —Coffee break (Rotunda)

10:30 a.m. —Session I continued (Grand Ballroom)

Thomas D. Fouch, presiding

Uranium ore genesis in the context of basin evolution, San Juan Basin, New Mexico *Christine E. Turner-Peterson and Neil S. Fishman*

Uranium-bearing solution-collapse breccia pipes in northern Arizona *Karen Wenrich and George H. Billingsley*

Geothermal systems in the Cascade Range *Michael L. Sorey, Steven E. Ingebritsen, and Robert H. Mariner*

Reservoir fluids of the Baca, New Mexico, geothermal field *A. H. Truesdell and C. J. Janik*

12:00 noon —Luncheon honoring Vincent E. McKelvey (Grand Salon)

Luncheon address by Raymond A. Price

"Cordilleran accretionary tectonics, the overthrust belt and energy resources—A Canadian perspective"

2:00 p.m. —Session II (Grand Ballroom)

H. J. Gluskoter, presiding

Allocyclic and autocyclic conditions of coal formation *C. Blaine Cecil*

Depositional controls on the geometry of the Wyodak-Anderson coal bed, northeastern Wyoming *Peter D. Warwick and Ronald W. Stanton*

Taphonomy of nonmarine mollusks as an indicator of alluvial-lacustrine sedimentation *John H. Hanley and Romeo M. Flores*

New approach to organic geochemical studies of the coalification process—Chemical and physical evolution of coalified logs as a function of rank *Patrick G. Hatcher*

3:20 p.m. —Coffee break (Rotunda)

3:50 p.m. —Session II continued (Grand Ballroom)

L. J. Patrick Muffler, presiding

Structure and petroleum potential of Palisades Roadless Area, Idaho-Wyoming thrust-belt salient near Jackson, Wyoming *Steven S. Oriel and David W. Moore*

Burial history and timing of thermal gas generation in Cretaceous rocks, eastern Uinta Basin, Utah—Evidence from Lopatin reconstruction *Janet K. Pitman and Karen J. Franczyk*

Evolution of oil-shale basins—Evidence from sulfur geochemistry *M. L. Tuttle and M. B. Goldhaber*

Fluid migration pathways—Evidence from thermal maturity mapping in southwestern Wyoming *B. E. Law, M. R. Lickus, and M. J. Pawlewicz*

7:30–10:00 p.m. —Keg and poster session (Ballroom and Rotunda)

Thursday, February 6, 1986

8:30 a.m. —Session III (Grand Ballroom)

Dudley D. Rice, presiding

GLORIA sidescan-sonar survey of the Western Mississippi Fan intraslope basins *B. A. McGregor, J. S. Schlee, and K. D. Klitgord*

Seismic structure and stratigraphy of the Western Florida Shelf *Mahlon M. Ball and Jim Leinbach*

Structural development of the southeastern margin of the Anadarko basin, Oklahoma *William J. Perry, Jr.*

Thermal maturity modeling and geochemical characterization of hydrocarbon source rocks, oils, and natural gases of the Anadarko basin *J. R. Hatch, D. D. Rice, R. C. Burruss, J. W. Schmoker, and J. L. Clayton*

Petroleum generation and migration in Lower Jurassic lacustrine sequences, Hartford basin, Connecticut and Massachusetts *Lisa M. Pratt, April K. Vuletich, and Robert C. Burruss*

10:10 a.m. —Coffee break (Rotunda)

10:30 a.m. —Session III continued
Dudley D. Rice, presiding

Marine cementation and early porosity loss in bank-margin carbonates—Examples from Enewetak *Robert B. Halley, Eugene A. Shinn, and Larry A. Beyer*

Magnetic minerals and hydrocarbon seepage—Possibilities for magnetic detection of oil fields *Richard L. Reynolds, Neil S. Fishman, Mark R. Hudson, J. A. Karachewski, and Martin B. Goldhaber*

Advances in understanding North Slope oil and gas accumulations *K. J. Bird, L. B. Magoon, and C. M. Molenaar*

Gas hydrates, North Slope of Alaska *T. S. Collett, K. J. Bird, L. B. Magoon, K. A. Kvenvolden, and G. E. Claypool*

Future hydrocarbon studies in the Bering Sea *Alan K. Cooper, Michael S. Marlow, and David W. Scholl*

SECOND ANNUAL V. E. McKELVEY FORUM—POSTER SESSIONS

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1	Accretion, subduction, and underplating in southern Alaska: Initial results from the Trans-Alaska Crustal Transect *Robert A. Page, David L. Campbell, George Plafker, Gary S. Fuis, Warren T. Nokleberg, Elizabeth L. Ambos, Walter D. Mooney, and Michael A. Fisher*
2	Geomorphology of the Western United States Exclusive Economic Zone—A GLORIA view *EEZ-Scan Group (David A. Cacchione, David E. Drake, Brian D. Edwards, Michael E. Field, James V. Gardner, Monty A. Hampton, Herman A. Karl, David S. McCulloch, Neil H. Kenyon, and Douglas G. Masson)*
3	GLORIA sidescan-sonar survey of the Western Mississippi Fan intraslope basins *B. A. McGregor, J. S. Schlee, and K. D. Klitgord*
4	Expert systems research and its application to energy studies *Katherine B. Krystinik*
5	The U.S. Geological Survey Oil Shale Program *Thomas D. Fouch and John R. Dyni*
6	Organic carbon accumulation and sulfur diagenesis in fine-grained Cretaceous rocks of the Western Interior of North America *Donald L. Gautier and Lisa M. Pratt*
7	Stratigraphic and structural framework, southern terminus of Rocky Mountains *Elmer H. Baltz*
8	Geometry and hydrocarbon appraisal of the Putnam thrust adjacent to the Snake River Plain near Blackfoot, Idaho *Karl S. Kellogg, Frank R. Hladky, and George A. Desborough*
9	Thermal maturity mapping of the United States *James G. Palacas*
10	Classification of clastic reservoirs for enhanced oil recovery *C. J. Schenk, J. W. Schmoker, and D. L. Gautier*
11	U.S. Geological Survey Onshore Oil and Gas Program *Dudley D. Rice*
12	An integrated approach using the computer in the geologic assessment of the hydrocarbon resource of the Powder River Basin, Wyoming and Montana *Richard F. Mast, James E. Fox, and Gordon L. Dolton*
13	Three statistical methods for estimating undiscovered resources based on the Minnelusa play, Powder River Basin *J. Houghton, E. Attanasi, G. Dolton, L. Drew, R. Mast, D. Root, and J. Schuenemeyer*
14	Fracture network flow *Christopher C. Barton*
15	Evaluating compositional trends in Miocene-Pliocene strata of south-central coastal California *Caroline M. Isaacs, Kathleen C. Stewart, and Larry L. Jackson*
16	The U.S. Geological Survey Evolution of Sedimentary Basins Program *Thomas D. Fouch, B. H. Kent, J. W. Schmoker, J. L. Ridgley, K. J. Englund, and K. J. Bird*

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18 The Shublik Formation—A model for deposition in an ancient marine upwelling zone
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19 Geochemical study of surface oil shows and potential source rocks in the Arctic National Wildlife Refuge (North Slope Alaska)
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20 Regional correlation sections across the North Slope of Alaska
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21 Conodont thermal maturation patterns in Paleozoic and Triassic rocks, northern Alaska—Geologic and exploration implications
Anita G. Harris, I. L. Tailleur, and H. Richard Lane

22 Tectonics—A first-order control of sediment distribution and hydrocarbon potential: Examples from the western margin of North America
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23 Tectonics and the potential for hydrocarbons in offshore basins of Western North America
Hugh McLean

24 Analysis of seismic reflection lines over Pacific convergent margins
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25 Potential gas generation in subducted sediments of the eastern Aleutian Trench area
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26 Continental margin mapping project, United States Atlantic margin—A synthesis of geological and geophysical data and interpretations
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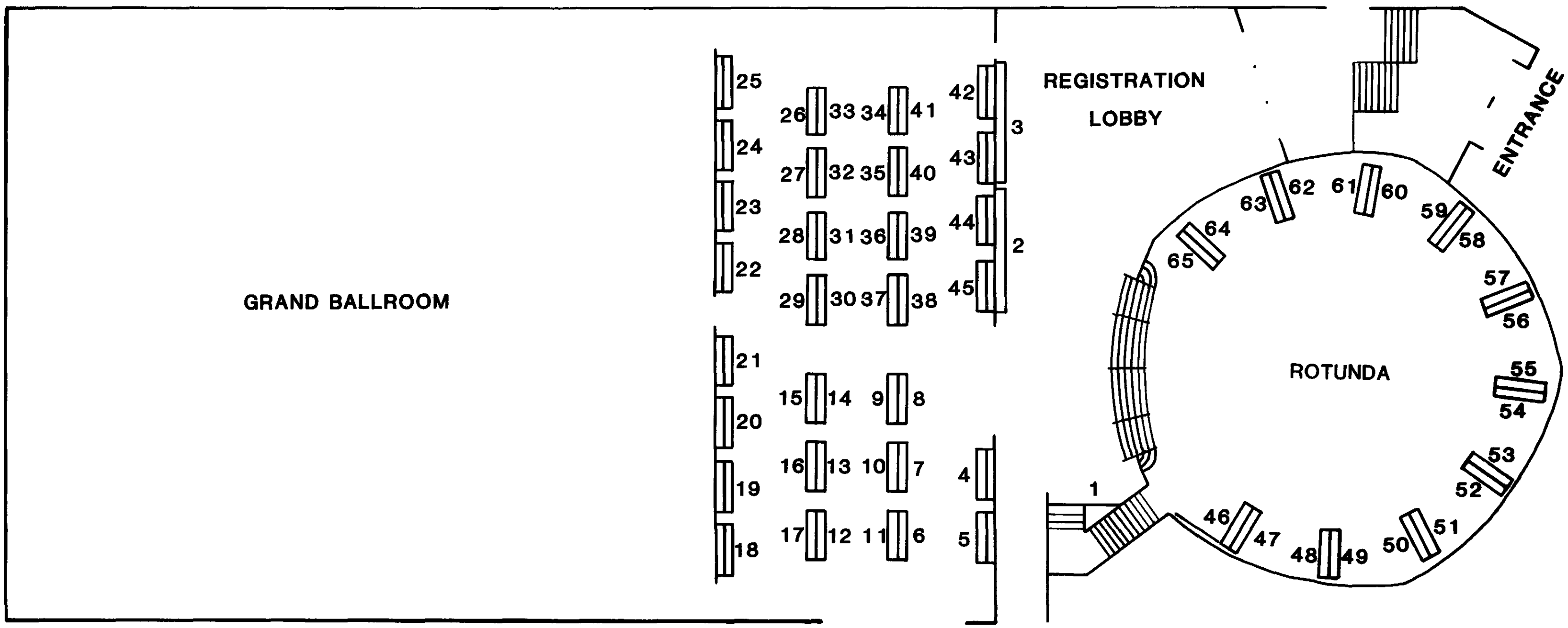
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FLOOR PLAN

Abbreviations used in this Circular:

EEZ—Exclusive Economic Zone
Ga—giga-annum (10^9 years ago)
Ma—mega-annum (10^6 years ago)
m.y.—10^6 years duration
STP—standard temperature and pressure
TCF—trillion cubic feet
bbl—barrel

In the term GLORIA sidescan system, GLORIA stands for Geological Long-Range Inclined Asdic

The use of trade names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

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GEOCHEMICAL STUDY OF SURFACE OIL SHOWS AND POTENTIAL SOURCE ROCKS IN THE ARCTIC NATIONAL WILDLIFE REFUGE (NORTH SLOPE ALASKA)

Donald E. Anders and Leslie B. Magoon

The presence of six oil seeps or oil-stained outcrops in the Arctic National Wildlife Refuge (ANWR) of northeastern Alaska indicates the possibility of commercial hydrocarbon occurrence in the subsurface. Interest in the resource potential of this region is heightened by the fact that ANWR is flanked by two important petroleum provinces, the Prudhoe Bay area on the west (estimated in-place reserves of 40–70 billion barrels of oil), and the McKenzie delta on the east (estimated in-place reserves of 740 million barrels). These productive areas adjacent to ANWR have quite different geology from each other, including different sources and geochemical character of their respective hydrocarbons. These differences make it impossible to extrapolate the geologic and geochemical relationships of the adjoining regions into the coastal plain of ANWR.

Organic carbon content, Rock-Eval pyrolysis, and vitrinite reflectance were used to evaluate the source rock quality and thermal maturity of five rock units within ANWR—the Shublik Formation, Kingak Shale, pebble shale, and bentonite and shale in the Colville Group. The average organic carbon content within these rock units is as follows: (1) 1.6 weight percent for the Triassic Shublik Formation; (2) 2.0 weight percent for the Jurassic and Lower Cretaceous Kingak Shale; (3) 3.0 weight percent for the Lower Cretaceous pebble shale; (4) 4.0 weight percent for the bentonite section of the Upper Cretaceous Colville Group; and (5) 2.0 weight percent for the Tertiary shale sequence and shale of the Upper Cretaceous Colville Group. The Cretaceous rock units in ANWR are thermally immature (vitrinite reflectance <0.5 percent) with respect to hydrocarbon generation on the coastal plain and thermally mature to overmature (vitrinite reflectance >1.0 percent) in the Sadlerochit and Shublik Mountains, where tectonic events have brought more deeply buried rocks to the surface. Rocks older than Cretaceous do not crop out in the coastal plain of ANWR and could not be evaluated. The oils collected from immature rocks in the coastal plain presumably migrated from a mature source.

In ANWR, organic matter type in the Tertiary section, the Lower Cretaceous pebble shale, and the Lower Cretaceous rocks of the upper unit of the Kingak Shale is predominantly type III (hydrogen index range 11–69 mg S_2/gC); whereas, the organic matter in the Lower Cretaceous bentonite-rich zone equivalent to part of the Colville Group is predominantly type II. The organic-matter type in the Jurassic unit of the lower Kingak Shale and the Triassic Shublik Formation could not be reliably determined because the only samples available for study (from the Sadlerochit and Shublik Mountains) are thermally overmature.

Based on comparison of the following geochemical attributes—stable carbon isotope ratios, tricyclic terpane ratios, pentacyclic:tricyclic terpane ratios, and saturate:aromatic hydrocarbon ratios, the ANWR oils can be divided into three genetic oil types, typified by (1) the oils from Augun Point, north and south Katakturuk River, and Jago River; (2) the oils from Manning Point; and (3) the oil from Kavik.

Oil-source rock correlation studies of carbon isotope ratios, tricyclic terpane ratios, and pentacyclic:tricyclic terpane ratios suggest that the most promising source rock for the Augun Point, Katakturuk River, and Jago River oil types is the type II bentonite unit equivalent to part of the Colville Group. Geochemically, the Manning Point and Kavik oil types are sufficiently different than the bitumens extracted from the five rock units assessed in this study so as to suggest sources that have not yet been evaluated.

Given the foregoing similarity of the organic matter in the Colville Group bentonite to the oils from Jago River, Katakturuk River, and Augun Point, inference can be made that stratigraphic traps within the Colville Group, such as the fine-grained lenticular turbidite sands, may have some limited reservoir potential, but the thicker Tertiary fluvial and marine sandstone sequences of the delta facies may be more favorable exploration targets.

SEISMIC STRUCTURE AND STRATIGRAPHY OF THE WESTERN FLORIDA SHELF

Mahlon M. Ball and Jim Leinbach

The U.S. Geological Survey has obtained 3,000 km of multichannel seismic-reflection data on the western Florida Shelf as part of its regional stratigraphic and structural framework studies in offshore territorial waters. These seismic lines were positioned to tie offshore well control to onshore wells in Florida and to the seismic network of the University of Texas (Texas Institute of Geophysics, Austin) over the deep Gulf Basin. The study reconciles offshore reflection data and well control with previous work based on onshore well studies and on gravity and magnetic data.

The definition of geologic "basement" is especially important in understanding the structure of the western Florida Platform. Onshore drilling in Florida, reported by R. S. Barnett in 1975, reveals a variety of basement rocks. These basement-rock types have been projected into the offshore largely on the basis of similar gravity and magnetic characteristics and trends, as noted by K. D. Klitgord and others in a 1984 study. Basement blocks are inferred to be bounded by (1) northwest-trending fracture zones that were transform faults during the Late Jurassic opening of the Gulf of Mexico and (2) northeast-trending hinge zones that separate rifted and intruded basement from relatively unfaulted continental blocks, as noted by K. D. Klitgord and others, in 1984. The rifted and intruded basement corresponds to transitional crust, tends to be structurally low, and is overlain by Mesozoic sedimentary basins.

Similar characteristics are suggested by the available seismic data. The seismic "basement" varies with changes in the magnetic and gravity data. In the northwest, relatively flat reflections from strata of the Mesozoic Apalachicola basin are separated by a prominent unconformity from more steeply dipping strata that are probably synrift in origin. A large basement fault inferred to represent a downdip continuation of the Gulf Basin's marginal fault zone is located at the northwestern extension of the Bahamas Fracture Zone. Toward the southeast, the reflection marking the basement-sediment contact rises onto the Middle Ground Arch. This reflection fades as velocity and density contrasts diminish between the onlapping Upper Jurassic strata and underlying Paleozoic sedimentary rocks. The apparent relief of the Middle Ground Arch in seismic-reflection sections is enhanced by the regional southeastward velocity increase in the Mesozoic sediments overlying the Paleozoic basement. This increase is a result of a decrease in clayey sediments that predominate in the Apalachicola basin and an increase in dense limestones, dolomites, and anhydrite in the Mesozoic sediments of the Florida carbonate province. Seismic sections crossing the Florida Platform escarpment demonstrate the shallowing of basement beneath the platform relative to that under the deep Gulf Basin.

The Apalachicola basin apparently contains a substantial thickness of Louann Salt. Our lines reveal an essentially flat basement reflection passing beneath an inferred salt pillow at Destin Dome. The dome is a northwest-trending anticline more than 80 km long and 30 km wide; it has relief of a kilometer on Lower Cretaceous rocks. The dome appears to be the result of a swell that was uplifted during the Late Cretaceous and early Cenozoic. Several smaller apparent salt swells with earlier growth histories than that of the Destin Dome are also present in Apalachicola basin. The Destin Dome has been and remains a petroleum exploration target with substantial potential.

To the southeast, in the Florida carbonate province, local structures consist of low-relief platform-interior patch reefs that are similar to the oil-producing structures of the Lower Cretaceous Sunniland Limestone trend. Regional erosional highs such as the Sarasota Arch are also present, but they are poorly defined by the seismic records.

Velocity surveys and lithologic descriptions from 4 key wells together with suites of sonic and density logs from 25 wells and the multichannel reflection lines connecting the key wells can be used to generate synthetic seismograms and to achieve optimum integration of the seismic and subsurface data. This approach is the basis for our correlation of basement, the top of the salt where present, the top of the Neocomian, the mid-Cretaceous unconformity, and the Cretaceous top throughout most of the western Florida Shelf north of lat 27° N.

STRATIGRAPHIC AND STRUCTURAL FRAMEWORK, SOUTHERN TERMINUS OF ROCKY MOUNTAINS, NEW MEXICO

Elmer H. Baltz

The Sangre de Cristo uplift of New Mexico and Colorado is the southernmost range of the Rockies, lying between the northern basins of the Neogene Rio Grande rift and the Laramide-age Raton and Las Vegas basins of the Great Plains. Within this structurally complex uplift, Precambrian, Mississippian, and Pennsylvanian rocks are exposed widely; Permian, Mesozoic, and Cenozoic rocks and sediments are exposed on its margins; and Cenozoic volcanic and intrusive rocks occur at places on the uplift and its margins. The structure and stratigraphy of the uplift and its bordering basins in New Mexico are being studied by detailed and reconnaissance mapping, biostratigraphy, subsurface methods, and analyses of regional gravity and aeromagnetic data. The studies, especially of Pennsylvanian rocks, suggest the existence of potential hydrocarbon sources and structural and stratigraphic traps.

In Pennsylvanian and Early Permian time the area of the present uplift, from about Taos, N. Mex., southward, and the area of the adjacent Las Vegas basin were parts of a deep structural basin in which synorogenic fine-grained to gravelly sandstone, thick gray shale, and carbonate rocks were deposited in complexly related marine and nonmarine environments. The Pennsylvanian rocks are absent locally at the south but are almost 7,000 ft thick at the north, both at outcrops and in the subsurface. The thickening is accompanied by pronounced regional and local facies changes. Mapping of lithostratigraphic and biostratigraphic units shows that the Pennsylvanian rocks can be subdivided into regionally persistent formations useful for determining Paleozoic and Cenozoic structure and useful for integrating regional surface and subsurface data to understand Paleozoic facies distribution. Newly recognized inter- and intraformational unconformities demonstrate several large Paleozoic, sediment-shedding, intrabasinal uplifts and complementary local sedimentary basins. Isopachs of several formations reveal the correspondence of some Paleozoic and Cenozoic local uplifts and synclinal basins and some faults; however, some exposed Paleozoic structures extend eastward into the subsurface of the Las Vegas basin. Pennsylvanian rocks on the west margin of the Sangre de Cristo uplift north and south of Santa Fe are scant remnants of those deposited on the flank of a major Paleozoic uplift that is now the western part of the Cenozoic uplift. Pennsylvanian rocks of several facies may thicken westward from the uplift into the subsurface of the Neogene Española Basin.

Theories of origin of the Cenozoic Sangre de Cristo uplift include: (1) vertical uplift along downward-steepening reverse faults; (2) volcanotectonic uplift; and (3) several to several tens of miles of thin-skinned overthrusting. Detailed mapping shows that the Cenozoic southeastern front of the uplift is a zone of northerly-trending, basement-cored, asymmetric, east-verging, anticlinal blocks. North of Las Vegas, for at least 30 mi, the eastern parts of these blocks were thrust eastward across the mainly overturned west limb of the Las Vegas basin along probable listric faults. The vertical separation on the top of the Precambrian between the Las Vegas basin and the frontal zone of the Sangre de Cristo uplift is about 5,000 ft at the south and about 15,000 ft at the north. Horizontal shortening at the south is about 3,000 ft and possibly more than 10,000 ft locally at the north near Mora, N. Mex.

The Cenozoic overthrusting probably created lengthy structural traps on the west margin of the Las Vegas basin in areas where Pennsylvanian rocks contain thick, potential hydrocarbon source rocks interlayered with potential reservoir rocks. In some places the Cenozoic structure may have enhanced preexisting Paleozoic traps. Untested stratigraphic traps probably exist on other margins of the Las Vegas basin.

PALEOCEANOGRAPHIC AND TECTONIC INFLUENCES ON THE DEPOSITION OF THE MONTEREY FORMATION OF CALIFORNIA

John A. Barron

A combination of oceanographic conditions and tectonic events shaped the deposition of the Monterey Formation, of Miocene age, the major petroleum source rock in California. The well-known abundant diatomaceous rocks in the Monterey are indicators of high biologic productivity, and diatoms may well be the original source for much of the petroleum of the Monterey. The biogenic-rich sediments of the Monterey are relatively free of detrital mineral grains, and closely resemble pelagic sediments of the deep sea.

The base of the Monterey at 17.5 Ma (late early Miocene) coincided with rising global sea level and with an increase in diatomaceous sediments throughout the North Pacific. The increase in biosiliceous sediments in the Pacific paralleled a decline in biosiliceous sediments in the Caribbean and low-latitude North Atlantic, which may have been caused by increased production of North Atlantic Deep Water in the latest early Miocene. With rising sea level, terrigenous sediments became largely isolated in inshore basins, while offshore basins received a steady rain of diatoms settling down from productive surface waters. Carbon isotope records in the Pacific and Indian Oceans record the storage of organic-rich sediments in the Monterey and equivalent diatomaceous rocks around the rim of the North Pacific by a pronounced +1.0 ‰ increase in $\delta^{13}C$ beginning at 17.5 Ma.

Polar cooling in the late middle Miocene and late Miocene was reflected by increased diatom productivity in the upper part of the Monterey, resulting from increased upwelling, in turn due to intensified circulation. Diatom fertility was high enough during the latest Miocene that the CCD (Calcium Carbonate Compensation Depth) was raised considerably, and upper Monterey rocks are essentially barren of foraminifers.

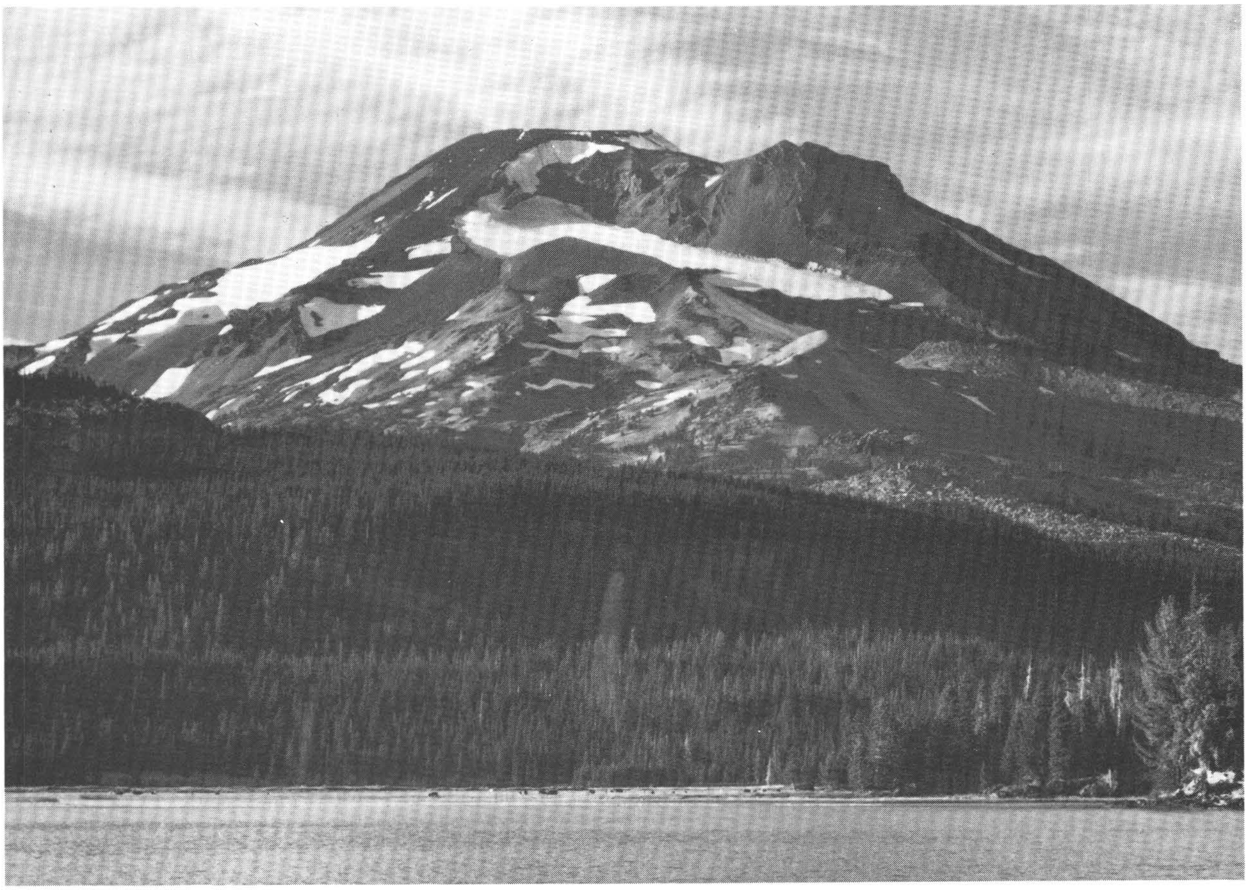
The top of the Monterey at about 6 Ma coincides with a major drop in sea level and is commonly marked by an unconformity. Sediments above the Monterey have an increased terrigenous component, presumably because lowered sea level resulted in channels being cut through to the outer basins, which allowed the transport of detritus. Carbon isotope records in the Pacific and Indian Oceans show a –1.0 ‰ shift in $\delta^{13}C$ at 6.2 Ma, signalling an end to the vast storage of organic-rich sediments in marginal reservoirs such as the Monterey.

The Monterey Formation was also influenced by tectonic events during its deposition. Initiation of transform faulting and extension along the California margin in the latest Oligocene and early Miocene caused the subsidence of basins that later received Monterey sediments. A major tectonic event at about 10–9 Ma, which included rotation of the Santa Barbara Basin and a change in Pacific plate rotation, is marked by an unconformity and (or) an interval of compressed sediment in most Monterey sections. Another change in plate motion at about 6 Ma may be expressed by the angular discordance seen between the Monterey and overlying rocks.

FRACTURE NETWORK FLOW

Christopher C. Barton

Fracture traces exposed on six 205- to 1,726-m^2 laterally separated, subhorizontal pavements in the same shallow-dipping Miocene ash-flow tuff at



South-southeast side of South Sister, Oregon, as viewed from across Sparks Lake. Photograph by Lyn Topinka, David A. Johnston Cascades Volcano Observatory, Vancouver, Wash., October 1984.

Yucca Mountain, southwestern Nevada, have been mapped at a scale of 1:50. The maps are two-dimensional sections through the three-dimensional network of strata-bound fractures. All fractures with trace lengths greater than 0.20 m were mapped. The distribution of fracture-trace lengths for all the pavements combined is log-normal. The fractures for all the pavements combined do not exhibit well-defined sets based on orientation.

Fractal characterization (from a 1982 study of B. B. Mandelbrot) of such complex fracture-trace networks may prove useful for modeling fracture flow and mechanical responses of fractured rock; therefore, an analysis of each of the six maps was done to test whether such networks are fractal. These networks proved to be fractal, and the fractal dimensions (D) are tightly clustered (1.10 to 1.18), even though visually the fracture networks appear quite different. An electric analog of a fracture network (see a 1985 study of P. R. LaPointe and J. A. Hudson) with a fractal dimension that we determined to be D=1.39 has a strongly directed flow anisotropy, a characteristic that is not obvious from the distribution of fracture strikes. The fractal analysis also indicates that the network patterns are self-similar (scale independent) over two orders of magnitude for trace lengths ranging from 0.20 to 25 m.

ADVANCES IN UNDERSTANDING NORTH SLOPE OIL AND GAS ACCUMULATIONS

K. J. Bird, L. B. Magoon, and C. M. Molenaar

The North Slope of Alaska petroleum province is an onshore-offshore region of complex geology covering an area of more than 100,000 mi^2 (260,000 km^2). Twenty-five oil and gas fields with in-place resources totaling more than 60 billion barrels of oil and 35 trillion cubic feet of gas have been discovered. Most North Slope oil and gas occur in a few large fields that are geographically concentrated within a relatively small area of the province, centered around Prudhoe Bay. The two producing fields, Prudhoe Bay and Kuparuk River, account for about 20 percent of daily United States oil production.

Petroleum prospective rocks on the North Slope consist of a Mississippian to Lower Cretaceous sequence derived from a northern provenance and a Lower Cretaceous to Holocene successor basin sequence derived from a southern provenance. These sequences are deformed along a foreland fold and thrust belt to the south and are relatively undeformed along a passive margin to the north. Volumes of oil are nearly equally distributed in reservoirs of these two sequences of rocks. Regional analysis indicates that the time of generation and the location of most North Slope oil and gas fields were controlled by Cretaceous and Tertiary tectonics and sedimentation.

Significant amounts of oil and gas are apparently yet to be discovered in this province, and most types of unconventional oil and gas resources are also present but as yet unevaluated; unconventional oil and gas resources include heavy oil or tar, oil shale, coalbed methane, tight gas sand, geopressured methane, and methane hydrates. Organic geochemical studies by industry and the USGS indicate that (1) two types of oil (and possibly several subtypes of each) are present, (2) Triassic and Jurassic source rocks are responsible for the most abundant oil type, and (3) Lower Cretaceous rocks are responsible for the other type—which accounts for only minor amounts of North Slope oil. In the coastal plain of the Arctic National Wildlife Refuge (ANWR), currently being evaluated, Triassic and Jurassic source rocks have probably been removed by Early Cretaceous erosion in much of the area. However, rich Lower and Upper Cretaceous source rocks, which are buried by as much as 4,000 m of Tertiary rocks in immediately adjacent areas, are more than adequate to generate significant amounts of oil in the ANWR, if the rocks are mature.

PROSPECTING DEPOSITS FOR PEAT RESOURCES IN THE UNITED STATES

Cornelia C. Cameron

Exploration during the past two or three decades has shown the presence of large resources of peat in a variety of deposits occurring widely in the United States. United States peat resources are estimated to be 340 billion short tons based on an average peat deposit depth of 7 feet, and bulk density averaging 15 pounds per cubic foot for peat with a moisture content of 35 percent. In 1983 the apparent demand for agricultural peat in the United States was 1,144,000 tons, of which domestic producers provided 62 percent. The anticipated additional use of peat as a fuel source increases the forecast of total demand to about 1.4 million tons in 1990 and 2 million tons in the year 2000. Alaska contains about one-half the estimated resource, much of which is frozen. Peat deposits in conterminous United States extend southward beyond the margin of continental glaciation along the Atlantic, Gulf, and Pacific Coastal lowlands, and at high altitudes in the Appalachian and Rocky Mountains and the Sierra Nevada. This geographic distribution, with corresponding variation in plant types, climates, and physiographic and geologic settings, is reflected in size and shape of deposits as well as in their trace-element and organic-matter content, amount of contaminants such as clastic sediments and air-fall volcanic material, and vulnerability to aerobic bacterial action.

Conceptual models have proven to be useful exploration tools in the evaluation of United States

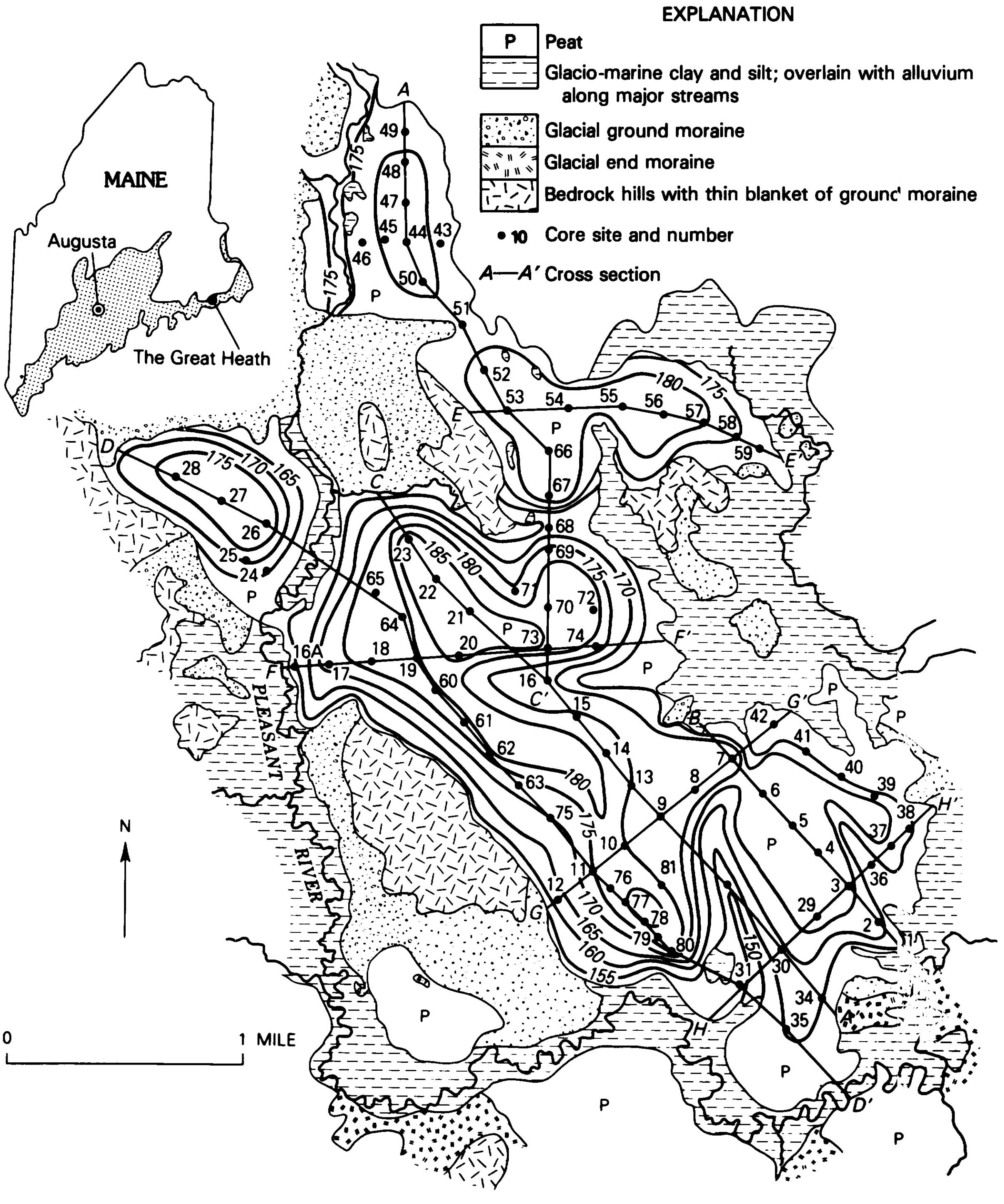


FIGURE 1.—Surficial geology of the Great Heath, Washington County, Maine. Inset shows location of the Great Heath, within the region of Maine covered by sea water during the period of maximum inundation (patterned). Lines of cross sections mentioned in text are shown but cross sections are omitted. Topographic contours in feet; contour interval 5 ft.

peat deposits, and their use can aid in predicting the possible uses of peat from a variety of geographic or geologic environments. To prepare a model one must select a deposit typical for a given geographic and geologic setting and determine as many of its geologic, physiographic, and chemical features as possible. Aerial photography and high-level infra-red photography are useful in such studies. Special coring devices such as Macaulay and Dutch augers and Davis peat samplers are used to determine thicknesses and stratigraphic variation and to collect samples for study of the depositional environment, fiber size, ash content, Btu, and trace-element content. A geologic map of the Great Heath (fig. 1) is part of a model for the domed heath type of peat deposit typical of the region in Maine that was covered by sea water during the late Pleistocene. This deposit is similar to a nearby deposit in the vicinity of Cherryfield, Maine, soon to be utilized for the manufacture of fuel pellets. Cross sections based on the surficial geology and core data show three types of organic material: (1) basal marsh muck resting on glaciomarine silts and clays, having a mean moisture-free ash content of 57.4 percent; (2) hemic peat having a mean moisture-free ash content of 4.9 percent; and (3) fibric peat having a mean moisture-free ash content of 1.25 percent. The Great Heath contains estimated resources of approximately 7 million short tons of peat (dry basis). As a potential fuel, this peat has low-sulfur and high-hydrogen contents; the Btu per pound ranges from 8,500 to 10,000 with the hemic type having values above 9,500.

ALLOCYCLIC AND AUTOCYCLIC CONDITIONS OF COAL FORMATION

C. Blaine Cecil

The spatial form and quality of coal beds are controlled by allocyclic and autocyclic processes operating during peat formation and subsequent diagenetic processes. Allocyclic processes are driven by energy changes external to a sedimentary system, such as eustatic changes in sea level, tectonic activity, and climate changes. Autocyclic processes are governed by the energy of the system, and include delta switching, stream meandering, and stream anastomosing. These key geologic processes must be qualified and quantified in a hierarchical geologic framework before lateral and vertical changes in coal beds and associated rocks can be predicted.

The USGS develops and tests predictive models of coal bed quality and spatial form through both coal quality and basin analysis programs. My current research within the basin analysis program indicates that during the peat stage of coal formation, allocyclic processes are the primary controls on the spatial form and quality; autocyclic processes are subordinate.

Extensive peat deposits develop when there is synergism among the allocyclic processes of climate, eustasy, and tectonics. Peat-forming conditions require maintenance of a water table at or near the peat surface, through some combination of an ever-wet climate, eustasy, and basin development. The extensive deposits of peat that are forming on the coastal areas of Sunda shelf of Malaysia and Indonesia are developing under these conditions. These deposits are ombrogenous, they are commonly domed, and plant communities are zoned. They are relatively low in ash and sulfur contents.

In areas of less rainfall, topogenous peat deposits might form, assuming that other basinal conditions are met. Topogenous peat deposits have planar surfaces, and they are dominated by ground and surface water, which is relatively high in dissolved solids content when compared to ombrogenous peat deposits. Plant communities tend to be random, and ash and sulfur contents are relatively high. If the water table is lowered by some combination of climate, sea level, or basinal conditions, then peat will not form. If the water table is elevated, by sea level rise, or subsidence, and (or) climate, the peat-forming environments may be replaced by marine or lacustrine environments.

Fluvial and deltaic systems that are primarily controlled by autocyclic processes are not conducive to the formation of extensive peat and coal deposits. During periods of aggradation of such systems, suspended and dissolved sediment loads preclude the formation of extensive, high-quality peat. Organic deposits formed under these physiochemical conditions will generally become carbonaceous shales in the rock record. Coal deposits that develop in response to autocyclic processes tend to be thin, and (or) discontinuous, and of poor quality.

Predictive genetic models, therefore, must be developed primarily on the basis of allocyclic processes; autocyclic processes are secondary. Depositional models are commonly unsuccessful predictors of the spatial form and quality because they are based on autocyclic processes of sedimentation, which predate or postdate the period of peat formation. Allocyclic models may be developed, quantified, and tested through additional integrated research focused on geochemical, mineralogical, and paleobotanical controls on peat genesis.

STABLE ISOTOPE GEOCHEMISTRY OF CALCITE AND PYRITE IN THE UPPER FREEPORT COAL BED, WEST CENTRAL PENNSYLVANIA

C. Blaine Cecil, Frank T. Dulong, Joseph F. Whelan, Ronald W. Stanton, and Elliot C. Spiker

Calcite and pyrite in coal can originate from multiple processes. Some of these processes operate during the peat stage of coal formation and some operate during burial and diagenesis. Our study focused on determining the origins of calcite and pyrite in coal using stable isotope geochemistry.

Three suites of samples were used: (1) nine samples of calcite collected from fractures (cleat) in the coal bed, from three different mines; (2) six samples from the underlying Upper Freeport Limestone Member of the Allegheny Formation and one sample from the Brush Creek Limestone of the Conemaugh Formation, which occurs approximately 100 feet (30 m) above the coal bed; and (3) samples derived from float-sink testing of the coal. Float-sink testing consisted of a 21-part size-gravity separation of each of three facies of the coal bed.

All samples were ashed in a low-temperature plasma asher. The mineralogic composition of the ash was estimated using X-ray diffraction. Calcite and pyrite were then separated from the ash using appropriate heavy liquids. These minerals were analyzed for their C, O, and S isotopic composition. The results indicate that at least three processes formed the calcite and two formed the pyrite.

The composition of the cleat calcite ($\delta^{13}C\bar{x}=+13\pm8‰$; $\delta^{18}O=21\pm1‰$) differs from that found in the Upper Freeport Limestone and the Brush Creek Limestone ($\delta^{13}C\bar{x}=-3\pm2‰$; $\delta^{18}O=25\pm2‰$). This indicates that the cleat calcite may have resulted from fermentation and methanogenesis reactions; it was not derived from calcareous strata associated with the coal bed.

X-ray diffraction analyses of float-sink separates indicated a bimodal distribution of calcite, which tended to be concentrated in the light and heavy gravity fractions. Calcite was also concentrated in the –100 mesh fraction. The isotopic composition of the calcite in the –100 mesh, and the 8×100, mesh-sink 1.8, size-gravity separates was similar to that of the cleat calcite.

Calcite in seven of the light gravity fractions had a relatively uniform $\delta^{13}C$ value of $-10\pm1‰$. Two anomalously high $\delta^{13}C$ values (+12.4, +5.4) were similar to the cleat calcite values. The $\delta^{18}O$ values range from +9.3 to +33.3‰. The relatively constant $\delta^{13}C$ values and the wide range in the oxygen isotope composition of the calcite in the light gravity fractions may indicate the presence of CO_2 derived from early bacterial sulfate reduction and later abiotic coalification reactions.

Differences in $\delta^{34}S$ values are strongly correlated with pyrite morphologies. Finely disseminated framboids and euhedral crystals are the dominant forms in the lowest facies of the coal bed; the $\delta^{34}S$ values are ≈1‰. Coarser, irregularly shaped pyrite is the dominant form in the uppermost facies; the $\delta^{34}S$ values are ≈10‰. That both pyrite morphologies occur in the middle facies is reflected by the range in $\delta^{34}S$ values from 0.2 to 8.5‰. Both types probably formed from H_2S produced during bacterial sulfate reduction. The differences in the $\delta^{34}S$ values indicate either different sulfate sources or reduction of a greater proportion of sulfate available during formation of the coarser pyrite.

PYRITE OF TRANSPORTED ORIGIN IN REWORKED FRAGMENTS FROM THE I COAL BED OF THE UPPER CRETACEOUS FERRON SANDSTONE MEMBER OF THE MANCOS SHALE, CENTRAL UTAH

E. C. T. Chao, Judith M. Back, and Jean A. Minkin

Except for cross-cutting secondary veinlets, pyrite in coal is usually considered to be of primary origin. The occurrence of primary pyrite in coal is interpreted to indicate that paleo-peat swamp conditions were anaerobic, because the formation

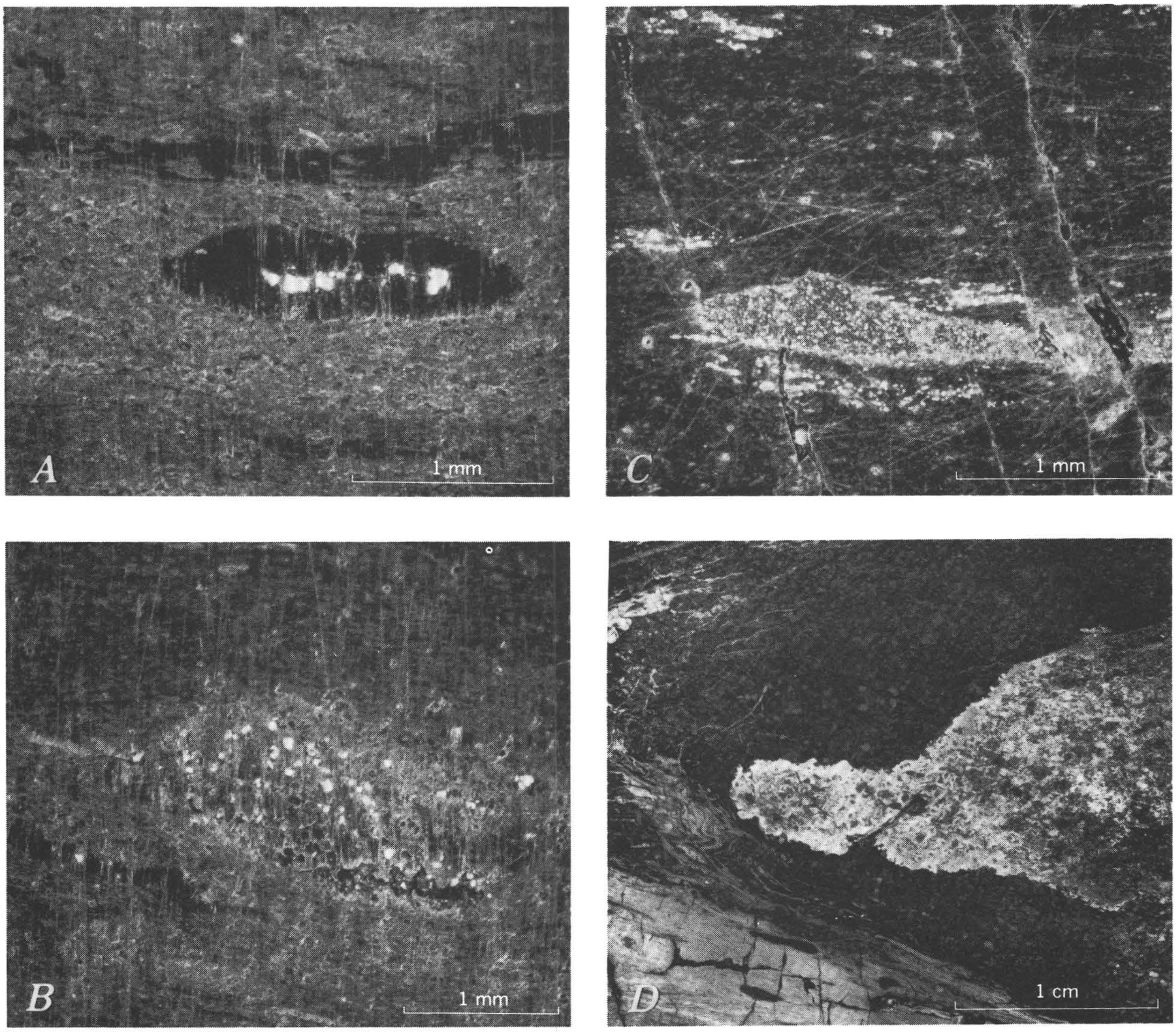


FIGURE 1.—Three types of pyrite-bearing fragments. *A*, vitrite fragment containing pyrite grains. Polished block (PB), diffuse illumination (DL). *B*, fragment consisting of vitrinite, semifusinite, and abundant pyrite grains. PB, DL. *C*, fragment consisting of fine-grained pyrite crystals and clay. PB, DL. *D*, massive pyrite replacing and encased in detrital coarse-grained clay. PB, DL.

of pyrite requires low Eh conditions (less than 100, as shown by Bass Becking in a 1960 study). We have observed pyrite enclosed in transported coaly and mineral-rich fragments within locally pyrite free coal matrices in the I coal bed of the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale of central Utah. The I coal bed has been interpreted by us (in 1983) as allochthonous, derived primarily from plant remains that were transported. Thus pyrite within the fragments must have formed elsewhere, probably in an anaerobic environment; the fragments were then reworked, transported, and deposited in the paleo-peat swamp at the locations corresponding to where they were found in the resulting coal bed.

Three types of pyrite-bearing fragments, each within a locally pyrite free matrix, have been recognized megascopically and interpreted to be of reworked origin in the I coal bed: (1) vitrite (fig. 1*A*) and vitrite gradational with inertite (fig. 1*B*) containing pyrite grains; (2) fine-grained crystalline pyrite and clay (fig. 1*C*); and (3) a large fragment (2×3 cm) of pyrite partially replacing coarse-grained clay, in turn completely surrounded by coarse-grained clay (fig. 1*D*). We suggest that this latter clay-encased fragment was transported as a trapped fragment in a mat of floating plant debris.

Textural characteristics suggest an allochthonous origin for the I coal bed; the presence of transported pyrite within it substantiates this interpretation.

PETROLOGIC STUDY OF THE CHARACTERISTICS OF COALS OF AUTOCHTHONOUS AND ALLOCHTHONOUS ORIGIN

E. C. T. Chao, Jean A. Minkin, Judith M. Back, and Sharon S. Crowley

"Autochthonous coals," as described by Teichmuller and Teichmuller in 1975 and 1982 studies, "develop from plants which after death form peat *in situ*. Allochthonous coals form from plant remains which were transported considerable distances from their original sites" to the sites of deposition and peat formation. The recognition of an allochthonous origin for some coals has been somewhat controversial. Moreover, distinctions between the characteristics of coals of autochthonous versus allochthonous origin have not been clearly defined.

On the basis of our research, the principal textural distinction between coal beds of autochthonous and allochthonous origins is that coals of autochthonous origin are finely laminated and well banded, whereas coals of allochthonous origin are coarsely fragmental and poorly banded. Allochthonous coal beds also are generally thicker, more variable in thickness, and more difficult to describe in terms of megascopic units than are autochthonous coal beds. Allochthonous coals generally have higher inertinite contents, higher mineral (ash) contents associated with inertinite-rich microlithotypes, and a more varied suite of minerals than do autochthonous coals. Based on our observations, as well as according to Teichmuller and Teichmuller's 1975 and 1982 studies, the presence of underclay may be used as evidence for the autochthonous origin of an overlying coal, and the lack of it for an allochthonous origin of a coal. Small amounts of coal of autochthonous origin may occur in a coal bed of predominantly allochthonous origin and vice versa. Of the coals we have studied, Pennsylvanian-age coals of the Eastern United States commonly are autochthonous. Examples of allochthonous coals can be found in coals of Mesozoic and Tertiary ages in the Western United States, such as the I (Utah) and Big George (Wyoming) coal beds.

Autochthonous coals were derived primarily from nontransported plant remains that accumulated in quiet and stagnant (anaerobic) peat swamps (conducive to pyrite formation), and probably resulted from relatively slow rates of plant accumulation. On the other hand, allochthonous coals were derived primarily from plant remains that were transported and deposited in more energetic paleohydrologic flow regimes and more aerobic peat swamp conditions (less favorable for pyrite formation). Plant accumulation in the formation of allochthonous coals may occur sporadically and at a faster rate than obtains for autochthonous coals.

GAS HYDRATES, NORTH SLOPE OF ALASKA

T. S. Collett, K. J. Bird, L. B. Magoon, K. A. Kvenvolden, and G. E. Claypool

Gas hydrates are crystalline compounds of water and gas in which the solid water lattice accommodates the gas molecules in a cagelike structure, or clathrate. The formation of gas hydrates in well bores and pipelines has been recognized since the 1930's. Recently, naturally occurring gas hydrate deposits have been detected in many arctic regions of the world, including western Siberia, the Mackenzie Delta of Canada, and the North Slope of Alaska. Some may have future economic importance.

Direct evidence of gas hydrates on the North Slope comes from a gas-hydrate-saturated core, and indirect evidence has been obtained from drilling and open-hole geophysical logs that indicate the presence of a number of gas-hydrate-saturated stratigraphic horizons in the Kuparuk River oil field. Recently completed work conducted as part of the U.S. Geological Survey/Department of Energy cooperative gas hydrate research project has delineated a thick zone within which gas hydrates would be potentially stable on the North Slope. Methane gas hydrate stability mapping has been done, using data from stabilized well-bore temperature surveys, ice-bearing permafrost depths and temperature data collected during wire-line well logging. This mapping indicates that gas hydrates may be stable to depths as great as 1,300 m in the Prudhoe Bay area.

To evaluate the history of gas hydrate formation on the North Slope, the chemistry of the in-place hydrates must be examined. Geochemical analysis of rock samples provided by ARCO/ALASKA from two wells in the Kuparuk River oil field reveals a complex gas chemistry within the shallow gas-hydrate-bearing horizons, with methane being the primary gas constituent. Well-log evaluation has revealed that one stratigraphically controlled gas hydrate occurrence appears to be reservoired with a shallow heavy oil. The physical properties of the heavy oils may be influenced by the presence of gas hydrates; changes in the reservoir characteristics, such as decreased oil gravities, represent an engineering problem that must be dealt with before production of these oils.

A series of modifications of normal well-log evaluation procedures has enabled us to conduct several preliminary gas hydrate resource evaluations of selected gas-hydrate-bearing horizons on the North Slope. The identified in-place deposits of gas hydrates appear to be laterally continuous, suggesting that gas hydrates may be an unconventional source of natural gas.

FUTURE HYDROCARBON STUDIES IN THE BERING SEA

Alan K. Cooper, Michael S. Marlow, and David W. Scholl

The Bering Sea can be divided into three hydrocarbon provinces: shelf, slope, and abyssal basin. The shelf province, the most studied, is underlain by large sedimentary basins that include Bristol Bay and St. George and Navarin basins. Geophysical and COST well data indicate that hydrocarbon potential of the shelf province is variable. Economic hydrocarbon deposits have not been discovered to 1985 in St. George and Navarin basins. Potential source-rocks of Eocene age and reservoir horizons of late Oligocene and early Miocene age are reported for Navarin basin. In St. George basin, good source-rocks and reservoir rocks were not encountered in the COST wells but may occur in other parts of the basin.

The slope and abyssal-basin provinces have received little attention from industry because of water depths (200–3,800 m) in the region. These provinces may contain prospective hydrocarbon habitats, based on the presence of 3- to 10-km-thick sedimentary deposits, fault and fold structures, and sedimentary onlaps, features similar to those of the shelf province. Further studies are planned by the USGS to look at the structure and evolution of these deep-water areas.

Beginning in 1986, the GLORIA long-range sonar system will be deployed in the Bering Sea to provide a detailed mosaic of sea-floor images that will cover the entire slope and abyssal-basin region. GLORIA, gravity, magnetic-gradiometer, and single-channel seismic-reflection data will be collected along ship tracklines at 20-km spacing, to provide the first systematic grid of geophysical data recorded over the deep-water regions. These data will be used to refine shallow- and deep-crustal models for the Bering Sea.

Proposals are presently being submitted to drill into the abyssal-basin and slope areas of the Bering Sea using the JOIDES drill-ship RESOLUTION. Drilling will be used to establish the age and origin of sedimentary and igneous rocks beneath the abyssal and slope areas of the Aleutian Basin. The drill cores should also provide information on the paleo-environmental, depositional, and structural history of the region prior to and after the growth of the Aleutian Ridge and isolation of the Bering Sea from the Pacific Ocean.

MEDICINE LAKE VOLCANO, CALIFORNIA, AND ITS GEOTHERMAL POTENTIAL

Julie M. Donnelly-Nolan

Medicine Lake Volcano is a Pleistocene and Holocene shield volcano about 50 km east-northeast of Mount Shasta, a location that places it just east of the main Cascade Range trend. The volume of Medicine Lake Volcano is estimated to be 600 km^3, larger even than Mount Shasta, which is the largest of the Cascade stratovolcanoes. The presence of several late Holocene silicic flows, together with intermittent rhyolitic volcanism during the last 1.25 m.y., has made Medicine Lake Volcano a prime target for geothermal energy exploration. Deep exploratory wells (>2 km) were drilled in the volcano's 7×12 km central caldera by private geothermal companies during 1984 and 1985.

Medicine Lake Volcano lies in an extensional back-arc setting behind the main Cascade volcanic arc. Major north-south-trending normal faults project under the volcano, and the dominant vent trend on the edifice is also north-south, indicating overall east-west extension. Open ground cracks on the surface of the volcano, some of which are associated with eruption of rhyolite, also suggest this extension direction.

This strongly extensional environment has permitted the eruption of tholeiitic basalt similar to mid-ocean ridge basalt. These very low K_2O magmas have erupted on the flank of the volcano throughout its history, as recently as late Holocene time. Derivative magmas are calc-alkaline and were produced by a variety of processes including crystal fractionation, assimilation, and mixing. Rhyolitic lavas are found on the upper parts of the edifice where they were typically erupted to the surface along dikes. One such late Holocene silicic eruption formed a single composite flow of rhyolite mingled with dacite, all of the dacite and part of the rhyolite containing chilled blobs of basaltic andesite. Zoned, contaminated, and mixed flows of various compositions are common at Medicine Lake Volcano. Typical flow volumes are less than 1.0 km^3, and commonly less than 0.1 km^3. No large-volume ash-flow tuffs are present; the only large-volume (5–10 km^3) eruptions are of primitive basalt.

Few patterns have been discerned in the chemical evolution of the volcano; in general (1) all compositions from 47 to 77 percent SiO_2 are present, although dacite is relatively rare; (2) the average composition is andesitic; and (3) individual eruptions at higher elevations on the edifice are likely to be small, evolved, and inhomogeneous, whereas the largest eruptions take place on the flanks of the volcano and are of homogeneous primitive basalt.

Although the geologic evidence for production of derivative magmas suggests that shallow magmatic processes have repeatedly produced small rhyolitic magma bodies, geologic and geophysical data indicate no large silicic magma chamber under the volcano. Instead, primitive basalt is intruded to shallow crustal levels beneath the volcano, forming a mafic intrusive complex recognized by seismic refraction and gravity studies. The apparent lack of a large silicic magma chamber does not lessen the importance of Medicine Lake Volcano as a geothermal resource, because heat continues to be supplied by intrusion of mafic magma into the shallow crust.

GEOMORPHOLOGY OF THE WESTERN UNITED STATES EXCLUSIVE ECONOMIC ZONE—A GLORIA VIEW

The EEZ-SCAN Group[1]

During summer 1984 the U.S. Geological Survey conducted a reconnaissance-scale survey of the entire western conterminous U.S. Exclusive Economic Zone (EEZ) using the Institute of Oceanographic Sciences (UK) GLORIA long-range sidescan sonar system. The digital data have been processed and compiled into a mosaic of the entire survey area, which extends from Mexico to Canada and seaward to the 200 nautical mile boundary. The area covers more than 750,000 km^2 and represents a major area for future exploration.

The sonar mosaic clearly shows the large-scale sediment bodies covering the sea floor (fig. 1). Submarine canyons incise the continental slope, and sediment fans that extend from them across the basins have an immense range of sizes and forms. Some channels on the sea floor are straight whereas others are highly sinuous, hinting that a variety of river-like processes occur on the sea floor. Vague to distinct variations in the reflectivity are probably related to differences in sediment composition. Any remaining notion of the deep sea floor as the repository of a uniform rain of sediment through the water column is soundly dispelled.

The small basins of the continental borderland off southern California show as low-reflectivity depressions encircled by intricately dissected steep slopes with small, immature submarine fans. In contrast, Monterey and Delgada submarine fans off central California are enormous features whose channels, depositional lobes, and sediment waves extend hundreds of kilometers from their sources. The scattered distribution of channels and depositional lobes attests to a dynamic history of sediment transport first to one area, then seemingly sudden abandonment in favor of some other

[1]David A. Cacchione, David E. Drake, Brian D. Edwards, Michael E. Field, James V. Gardner, Monty A. Hampton, Herman A. Karl, David S. McCulloch (all of USGS), and Neil H. Kenyon and Douglas G. Masson (Institute of Oceanographic Sciences, Wormley, United Kingdom.)

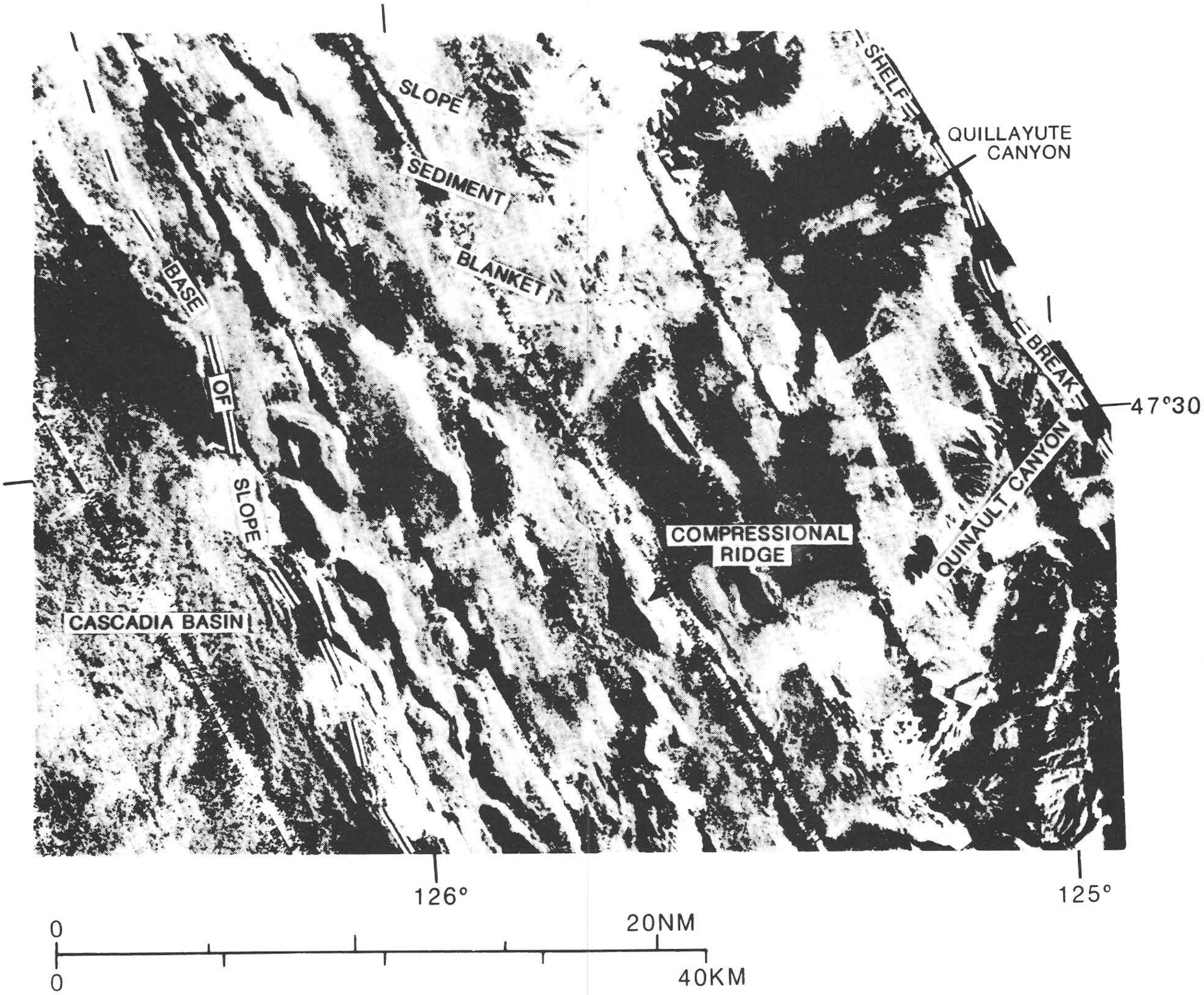


FIGURE 1.—A segment of the continental slope off the State of Washington. Shelf break is at a water depth of about 200 m, and base of slope is at about 2,500 m. Tectonic, erosional, and sedimentary features determine slope morphology.

course. The records show clear examples of basement ridges that block sediment dispersal, and sediment slides and associated mass-flow deposits that alter sediment-transport pathways.

Another very striking aspect of the mosaic is its expression of the regional geologic diversity that exists along the Western United States margin. For example, the contrast between the transform and convergent tectonic regimes south and north of Cape Mendocino, respectively, is obvious at a glance.

The continental slope in the region of convergent tectonics is crumpled into numerous folds that are shown as discontinuous ridges on the mosaics. Submarine canyons and blankets of sediment modify the steep compressional-ridge topography, the former tending to dissect and complicate it and the latter tending to smooth and simplify it.

Astoria and Nitinat submarine fans cover nearly the entire sea floor of Cascadia Basin north of Blanco Fracture Zone and east of Juan de Fuca Ridge. The fans merge along a common boundary and cannot be separated from one another on the mosaic. The distinct depositional lobes that characterize the large fans farther south are absent here. Close observation reveals a modern and relict sea-floor drainage system that includes lengthy channel-levee complexes extending from the apex of each fan, segments of abandoned channels, and scroll patterns that mark the former position of channels and document their wandering nature.

The extent and continuity of features such as submarine fans, sea-floor channels, and debris flows can be easily delineated, which will lead to modifications of depositional models inferred from previous investigations. The mosaic will be an invaluable base for deciphering geologic structures and processes at and beneath the sea floor, for planning marine scientific expeditions, and for making optimum decisions regarding use of the EEZ.

PROSPECTING FOR SHALLOW MAGMA CHAMBERS IN THE CASCADE RANGE USING SEISMIC TOMOGRAPHY

John R. Evans, Douglas A. Stauber, and Phillip B. Dawson

In the Cascade Range no seismic method has successfully delineated a magma chamber, though several methods successfully applied to other regions have been tried. Nevertheless, the area has high heat flow and abundant young volcanic rock—magma clearly is being generated and with a wide range of silica content. The possibility that Cascades magma chambers simply are smaller than continental silicic chambers successfully imaged with previous seismic methods prompted the use of the imaging method described here. This method is capable of resolving, in three dimensions, velocity anomalies as small as 1 km^3 in the upper 4–6 km of the crust even when they are part of complex structures that make reflection seismology impractical.

At Newberry volcano, Oregon, a dense two-dimensional array of 120 seismographs was deployed over the caldera and summit, and nine chemical explosions were detonated at distances of 30 to 90 km from the array. These explosions produced *Pg* and reflected *P* phases propagating upward beneath the array from many different azimuths. Residuals to a linear least-squares traveltime fit exhibited a ring of early arrivals coincident with the caldera ring fractures for all explosion azimuths, plus a small region of delays consistently on the far side of the caldera from each explosion.

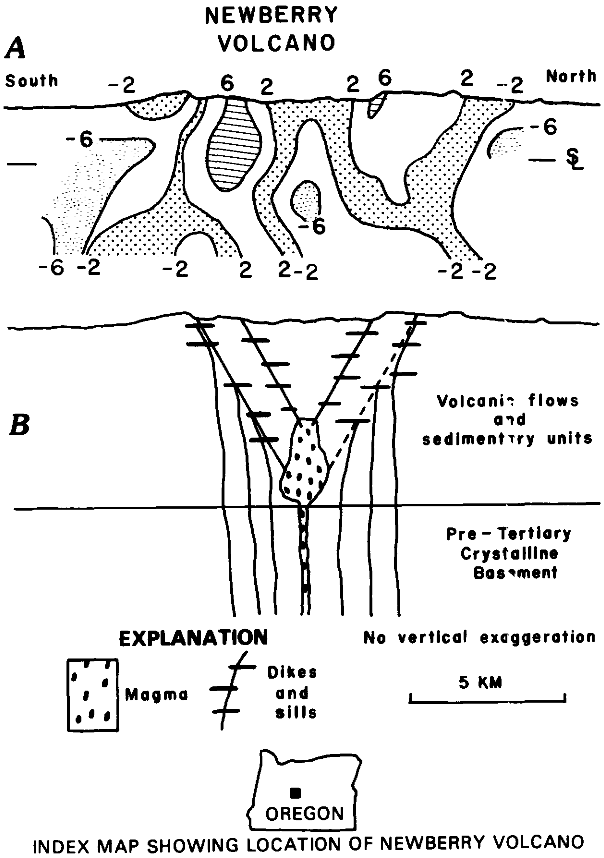


FIGURE 1.—Models of Newberry volcano, Oregon. *A*, tomographic velocity perturbation contours in percent of mean velocity (positive fast); *B*, interpretive model.

Both a simple geometric interpretation and a damped-least-squares inversion of these *Pg* and reflected-phase residuals reveal a ring of high-velocity material around the ring fractures and extending from near the surface to a depth of 3 or 4 km (fig. 1*A*). About 3 km depth under the center of the caldera is a small (approximately 1 km^3) low-velocity anomaly that causes the azimuth-dependent delay. This velocity structure is interpreted, in part, as a ring of crystalline intrusive rocks emplaced along the caldera ring-fracture system (fig. 1*B*). The deeper, low-velocity feature may be a small (probably silicic) magma chamber, or may be porous flows, breccias, and sediments downfaulted by the ring fractures.

Both features may make good geothermal targets. The ring intrusions may include hot recently solidified rocks and the ring fractures may serve to channel water. The low-velocity material may be the main shallow heat source, or a porous medium and good aquifer in an area known to exhibit high well-bottom temperatures.

A similar experiment is in preparation for Medicine Lake volcano, northern California. A dense array of 140 seismographs will be deployed across the caldera, summit, and youngest silicic flows to receive *Pg* from eight azimuths. Preliminary results from this experiment should be available in early 1986.

GEOTHERMAL SIGNIFICANCE OF AN EXTENSIVE CONDUCTOR BENEATH NEWBERRY VOLCANO, OREGON

D. V. Fitterman, R. J. Bisdorf, W. D. Stanley, and A. A. R. Zohdy

Newberry Volcano is a large Quaternary volcano located in central Oregon, ranging from basaltic to rhyolitic composition. It is composed of flows, ash-flow and air-fall tuffs, domes, and alluvium. Several hundred cinder cones and fissure vents dot its flanks. Extensive evidence of young, rhyolitic volcanism suggests that a geothermal reservoir might be associated with the volcano; high observed temperatures in the USGS Newberry 2 test hole (265°C at 930 m) in the caldera support this idea. Extensive geophysical work has been carried out on and around Newberry Volcano in an attempt to characterize a potential geothermal reservoir. The electrical techniques used include transient electromagnetic, Schlumberger, and magnetotelluric (MT) soundings; all these methods present a consistent picture. The data indicate two regions, divided approximately by the caldera boundary. Inside the caldera the geoelectrical section is characterized by moderate resistivities (50–200 ohm-m) to a depth of about 400 m, corresponding to lacustrine deposits and fragmental volcanic rocks, as determined by drilling. Beneath this layer, the resistivity decreases significantly to values of from 2 ohm-m to 50 ohm-m. Comparison of the temperature logs from the Newberry 2 well with the interpreted electrical section shows that this decrease in resistivity occurs at about the same depth as a high-temperature convective region. High-permeability lava flows and breccia allow fluid convection and lower resistivities.

Outside the caldera a very resistive surface layer (500–10,000 ohm-m) is underlain by a conductor (10–100 ohm-m) starting at depths from 300 m to 800 m. Below the conductor at depths from 1.5 km to 4.1 km, the MT soundings indicate the presence of resistive (>200 ohm-m) electrical basement, which is interpreted to be pre-Tertiary intrusive rocks. With the exception of a region adjacent to the west edge of the caldera, the conductor deepens away from the caldera; just west of the caldera, the conductor varies in depth from 300 m to 400 m. MT surveys have identified the conductor as a regional feature which extends over much of the High Cascades and eastern Oregon. Because any geothermal development will be restricted to regions outside the caldera, it is important to know if this conductor indicates the presence of hot fluids as observed in the caldera. There are several possible explanations of the extra-caldera conductor. Increased water saturation with depth is an unlikely explanation, because fresh, meteoric water is resistive, and at greater distances from the volcano, the top of the conductor occurs below the regional water table. On the flanks of the volcano, alteration of the pre-Newberry and Newberry rocks is the most likely mechanism to explain the conductor.

We believe that the conductor inside the caldera suggests the presence of a potential geothermal reservoir. The shallow conductive region just west of the caldera may have been produced by extensive alteration assocated with a hydrothermal system and thus represents a good geothermal target. Elsewhere on the flanks of the volcano, alteration by heat from the numerous cones and vents causes the conductor, which is not considered to be a geothermal target. Further from the volcano, the conductor is thought to be slightly altered Tertiary volcanics and Tertiary-Mesozoic sedimentary rocks.

ORGANIC CARBON ACCUMULATION AND SULFUR DIAGENESIS IN FINE-GRAINED CRETACEOUS ROCKS OF THE WESTERN INTERIOR OF NORTH AMERICA

Donald L. Gautier and Lisa M. Pratt

Fine-grained, organic carbon-rich Cretaceous rocks are an important source for petroleum in the Western Interior. These carbon-rich rocks can be classified as occurring in calcareous and noncalcareous systems. To gain a better understanding of organic matter accumulation and preservation, we have examined the sedimentology and geochemistry of organic matter and sulfur-bearing constituents of these two systems.

The content of organic carbon is inversely proportional to sedimentation rate in most fine-grained Cretaceous rocks of the Western Interior, and rates of organic-carbon accumulation were similar in organic carbon-rich rocks of both calcareous and noncalcareous systems. Rocks containing more than 4 weight percent organic carbon were deposited at rates of less than 10 m/m.y.; at higher sedimentation rates dilution by calcareous or noncalcareous constituents resulted in lower organic carbon content but not in lower organic carbon accumulation rates. The type of organic matter preserved is controlled by the intensity of aerobic diagenesis and by the influx of terrestrial organic matter.

Processes of sulfur diagenesis are sensitive to the degree of bottom-water oxygenation and bioturbation, and to how much organic matter is present and how readily it metabolizes. Consequently, isotopic ratios of pyrite sulfur and sulfur:carbon ratios are particularly useful in interpreting conditions of deposition and early diagenesis in the Cretaceous rocks of the Western Interior.

Among noncalcareous rocks, $\delta^{34}S$ of pyrite sulfur varies systematically with oxygenation in the depositional environment. Laminated shales with more than 4 percent organic carbon contain disseminated pyrite that is strongly depleted in ^{34}S ($\delta^{34}S = -31$ ‰) and their organic matter is hydrogen rich. In contrast, samples with less than 1.5 percent organic carbon are intensely bioturbated, have pyrite that is much less depleted in ^{34}S ($\delta^{34}S = -12.4$ ‰); their organic matter is hydrogen poor.

Pyrite in limestone concretions displays systematic sulfur isotopic values ranging from −18 ‰ on the margins to +16 ‰ in the center. Such a wide range, in contrast to the uniform values of surrounding shales (< 24 ‰), illustrates the extent to which concretion formation occurs as a closed system, and suggests that sulfur isotopic information from concretions should not be directly used in interpreting depositional and early diagenetic conditions.

Sulfur:carbon ratios in noncalcareous rocks are much higher than in organic-rich rocks of the calcareous system. This relationship suggests that either (1) the organic carbon-rich shales in the calcareous system accumulated beneath anoxic but not sulfidic bottom waters, whereas the noncalcareous, organic carbon-rich shales accumulated beneath bottom waters that were both anoxic and sulfidic, or (2) that the carbonate system was iron limited. Sulfur diagenesis is thus directly related to quality of hydrocarbon source rocks. Investigations of the sulfur system lead to better understanding of the conditions of oil and gas generation.

GENESIS AND IDENTIFICATION OF THE COLORADO PLATEAU URANIUM PROVINCE

Harry C. Granger, Warren I. Finch, Fred Peterson, Morris W. Green, Richard F. Sanford, C. S. Bromfield, and F. Allan Hills

The Colorado Plateau Uranium Province (CPUP) occupies a large part of the Colorado Plateaus physiographic province, from which it derived its name. It corresponds broadly to the area of major uranium deposits within Pennsylvanian through Jurassic sedimentary rocks in the province. In contrast, the edges of the CPUP as well as adjacent areas are either devoid of deposits or contain only minor deposits in either Tertiary volcanic and sedimentary rocks or Precambrian basement rocks.

Orthogonal sets of lineaments trending northeast and northwest across the region reflect structures that were periodically active in late Paleozoic through Mesozoic time and which exerted significant control on the positions of contemporaneous intracratonic basins and related sedimentary facies. Fluvial sandstone facies, in particular, contain most of the uranium deposits, and fine-grained volcaniclastic rocks overlying the sandstones are presumed to be the source of much of the uranium. Both structural features and sedimentary facies controlled the flow of ore-forming ground water.

Isotopic age determinations suggest that the major deposit types, distinguished by host formation, form, and mineral assemblage, resulted from three separate mineralizing episodes. The first was a major, widespread episode at about the end of Triassic time that resulted in deposits of the Coconino/Supai, Cutler, and Chinle types; the second was a minor localized episode in Middle Juras-

Aerial view, west side of Mount Rainier, Washington State. Photograph by Lyn Topinka, David A. Johnston Cascades Volcano Observatory, Vancouver, Wash., September 1977.

sic time that created deposits of the Todilto and, perhaps, Entrada types; and the third and dominant episode occurred at about the beginning of Cretaceous time and created the Westwater Canyon and Salt Wash types. Each of the two major episodes followed the only two massive accumulations of volcaniclastic strata in the region. This volcanic debris was derived from volcanic arcs far to the south and west and, as already noted, is believed to be the source of much of the uranium in the deposits.

Most geologic characteristics of the CPUP are not unique to the Colorado Plateaus province, but together they caused episodic uranium mineralization. The essential characteristics were (1) existence of a relatively stable continental foreland, (2) accumulation of continental host rocks, (3) a contemporaneous volcanic (or granitic) uranium source, (4) uraniferous shallow meteoric ground water derived from the volcanic or granitic detritus, (5) localization of uranium by adsorption and (or) reduction from uraniferous ground water either (a) percolating through a reducing environment imposed by degrading organic matter and hydrogen sulfide, or (b) encountering upwelling, deeply circulated, saline ground water at an interface within reduced host rocks, and (6) preservation promoted by crustal stability and long-term burial.

Details of the mineralizing processes are still not known and remain controversial. The uranium deposits of Mesozoic age in the Colorado Plateaus province, however, seem to have morphologic, mineralogic, and genetic characteristics that distinguish them from other known deposits, worldwide.

GEOLOGY AND GEOCHEMISTRY OF THE PRECAMBRIAN ROCKS OF THE READING PRONG, NEW YORK AND NEW JERSEY—IMPLICATIONS FOR THE GENESIS OF IRON-URANIUM-RARE EARTH DEPOSITS

Linda C. Gundersen

The Hudson Highlands and New Jersey Highlands, which make up the northern part of the Reading Prong, are complexly deformed, Grenville-age metamorphic rocks, typical of the upper amphibolite–lower granulite facies of regional metamorphism. Four major stratigraphic units have been recognized in these rocks: (A) a calc-silicate gneiss, consisting of a basal hornblende amphibolite and pyroxene gneiss with minor quartz-feldspar gneiss, marble, and allanite and scapolite-bearing gneisses; (B) a quartz-oligoclase gneiss with minor hornblende and pyroxene amphibolite; (C) a hornblende gneiss; and (D) a metasedimentary sequence consisting of graphitic quartz-feldspar gneiss, graphitic biotite gneiss, biotite-garnet gneiss, and minor hornblende-feldspar gneiss, marble, and pyroxene gneiss. Magnetite deposits, from which iron was produced in the 18th and 19th centuries, occur as concordant layers within the calc-silicate and hornblende gneiss throughout the Reading Prong. Individual magnetite trends are traceable along strike for 1–15 km and are in places associated with high concentrations of uranium and rare-earth elements.

Detailed geologic mapping, petrography, and major and trace-element analyses of both outcrop samples and samples selected from over 9,000 feet of drill core from the Greenwood Lake quadrangle, along with chemical analyses compiled from the literature, have led to the following observations and conclusions:

1. Rocks identified as volcanic, based on stratigraphic position and whole-rock chemistry (the quartz-oligoclase gneiss, pyroxene gneiss, and hornblende and amphibolite gneiss), were plotted using the methods of Irvine and Baragar's 1971 study. They define a calc-alkaline trend with a minor tholeiitic component, suggesting that they originated in a mature marginal marine basin. All other rock types were plotted in the same manner and display no apparent trends.

2. Magnetite occurs as elongate bodies in the cores of folds or as thick sequences of alternating bands with quartz and pyroxene, suggesting it was originally banded iron-formation. Iron and copper sulfides are present in variable amounts.

3. Ore-grade concentrations of uraninite are stratabound within magnetite layers in a number of the deposits. Uraninite crystals that vary in size from several micrometers to several millimeters across occur as inclusions and along grain boundaries of diopside, magnetite, allanite, and sphene. Conversely, magnetite and sphene can also be found within uraninite.

4. High concentrations of rare-earth elements resulting from the presence of layers of xenotime and monazite are found in the metasedimentary rocks. Pyroxene gneiss and hornblende gneiss close to the magnetite mines contain anomalously large amounts of light rare-earth elements commonly occurring in allanite. Magnetite ore also contains large amounts of light rare-earth elements occurring in apatite and allanite.

The rock sequence and mineral deposits just described may have originally been deposited in a marginal marine basin as (A) basic to intermediate volcanics, volcaniclastic and carbonate sediments, and exhalative iron, sulfide, and uranium-rich horizons; (B) acidic volcanics; (C) basic volcanics and exhalative iron, sulfide, and uranium-rich horizons; (D) acidic volcaniclastics, carbonaceous pelitic sediments with rare-earth element-rich horizons, and carbonates. Rare-earth element enrichment of rocks close to the magnetite deposits may have resulted from the circulation of CO_2-rich fluids during Grenville-age metamorphism.

MARINE CEMENTATION AND EARLY POROSITY LOSS IN BANK-MARGIN CARBONATES—EXAMPLES FROM ENEWETAK

Robert B. Halley, Eugene A. Shinn, and Larry A. Beyer

Marine cements commonly occlude pore space in carbonate rocks of reef and other bank-margin facies. Study of Miocene and younger carbonates on Enewetak Atoll during 1984–85 reinforces observations from more ancient rocks that marine cementation is more active on margins of carbonate banks than within bank interiors.

Surficial intergranular marine cementation occurs on the rim of Enewetak Atoll, as evidenced by lithified reef rubble that extends up to 2 km lagoonward and forms a back-reef, cemented surface up to a few meters thick. Marine-cemented, low-porosity rock is exposed by a submarine rockfall on the northern edge of the atoll that left a scarp extending several hundred meters deep in the bank margin. Massive marine cementation extends down the seaward slope of the atoll to depths greater than 350 m. In addition to intergranular cementation, marine cement as thick as several centimeters coats voids and fractures in bank-margin sediments. Massive marine cementation is evident into the margin as far as the scarp extends but was not found in a drill hole about 1 km lagoonward of the bank margin.

Core drilling during 1985 in the lagoon confirmed earlier observations that marine cements are scarce and account for little porosity loss in the bank interior. High porosity, typical of modern, unconsolidated, carbonate sediments, characterizes the lagoon cores; porosity is high for one of two reasons: (1) sediments have remained largely unaltered, retaining metastable mineralogy and original porosity; or (2) sediments have altered in fresh water, during which porosity loss due to calcite cementation is largely compensated by secondary porosity development through aragonite dissolution. The latter events occur during sea-level low stands (glacial periods) when the marine sediments of the atoll are exposed to meteoric-water diagenesis. The high porosity of lagoon cores is evident in thin sections, hand samples and density logs, and occurs in marked contrast to the low-porosity, marine-cemented limestones of the bank margin.

Carbonate platform margins have generally been favorable sites for oil and gas exploration; numerous hydrocarbon reservoirs have been found in these facies during the last 50 years. Within platform margins, marine cementation has adversely affected the reservoir quality of carbonate hydrocarbon reservoirs of many periods and is particularly important for reservoirs of Devonian, Permian, and Cretaceous age in North America. The marine cementation pattern from Enewetak and other modern and ancient carbonate platforms suggests the outermost platform edge may be unfavorable for the development of reservoir rocks due to marine cementation and early porosity loss.

TAPHONOMY OF NONMARINE MOLLUSKS AS AN INDICATOR OF ALLUVIAL-LACUSTRINE SEDIMENTATION

John H. Hanley and Romeo M. Flores

Depositional processes and paleoenvironments are readily interpreted from the taphonomy of freshwater mollusk assemblages in the Tongue River Member of the Fort Union Formation (Paleocene), in the northern Powder River Basin, Wyoming and Montana. The composition, species abundances, and spatial and temporal distribution of these assemblages were controlled not only by the environments in which the mollusks lived, but also by the depositional processes that affected the mollusks after death and before final burial (for example, transport, reworking and concentration of shells, and mixing of faunal elements from discrete habitats). These post-mortem processes produced a taphonomic "overprint" on assemblage characteristics that directly reflects alluvial-lacustrine sedimentation. The "overprint" can be interpreted through outcrop analysis of the biofabric, that is, the orientation, fragmentation, size sorting, abrasion, density, and dispersion of shells; the nature and extent of shell infilling; and the ratio of articulated to disarticulated bivalves.

Studies of mollusk taphonomy draw upon and augment sedimentologic studies. For example, post-mortem depositional processes that affected mollusk assemblages are revealed by sedimentologic characteristics such as lithology, stratification sequences, and bed configurations. Taphonomic interpretations are based in part upon these characteristics, but emphasize the sedimentology of mollusk shells through interpretation of the biofabric of assemblages.

In the study of the alluvial-lacustrine Tongue River Member, we used taphonomy in conjunction with other paleoecological criteria (composition, species abundances, and distribution of assemblages) to differentiate in-place, reworked, transported, and ecologically mixed mollusk assemblages. Our research defines paleontologic criteria for recognition of the varied environments in which these assemblages were deposited: large flood-basin lakes (on and off shore), small flood-basin lakes, crevasse-splay feeder channels, distal crevasse splays, and lake-crevasse deltas. The results of our studies indicate that taphonomy of mollusk assemblages—a heretofore underappreciated tool for paleoenvironmental interpretation—augments sedimentology for differentiating alluvial-lacustrine environments. Integration of paleoecology and sedimentology provides interdisciplinary criteria for interpretation of the paleoenvironmental framework of coal-forming environments, paleogeographic relations, and modeling the evolution of Tongue River Member deposition.

CONODONT THERMAL MATURATION PATTERNS IN PALEOZOIC AND TRIASSIC ROCKS, NORTHERN ALASKA—GEOLOGIC AND EXPLORATION IMPLICATIONS

Anita G. Harris, I. L. Tailleur, and H. Richard Lane[2]

The Paleozoic through Jurassic stratigraphic sequence in the Brooks Range, northern Alaska, consists chiefly of platformal to intraplatform basin deposits 1–5 km thick. This comparatively thin sequence of heterogeneous lithologies was tectonically disrupted and shortened at least 600 km to form a stack of allochthons that were transported relatively northward and emplaced during earliest Cretaceous time. The Seward Peninsula appears to be a southwestern continuation of Brooks Range geology. Most of the western ⅕ of the Seward Peninsula contains 4–5 km of unmetamorphosed platformal, dominantly shallow water carbonate rocks of Early Ordovician through Devonian age. Eastward, these rocks are thrust onto a blueschist terrane of mafic volcanogenic and clastic deposits and mixed carbonate and clastic rocks of probable Ordovician through Silurian age. Adjacent to and possibly infolded with these rocks are metamorphosed shallow-water carbonates of Cambrian through Devonian age similar to the rocks of the western Seward Peninsula.

Cambrian through Triassic rocks make up at least 40 percent of the surface bedrock in northern Alaska, chiefly in the Brooks Range and Seward Peninsula. Thermal patterns in these rocks are based on conodont color alteration indices (CAI) from 2,000 collections representing 450 localities. These patterns show: (1) a gradual increase in thermal level from the northern margin of the Brooks Range to about ¾ of the distance across the range (from CAI 1 to 5.5 and above); (2) a belt of mixed high values (CAI 4.5 to 7) along the south border of the range; (3) thermal levels in surface and subsurface samples that are related to tectonic burial and not prethrust burial metamorphism, because CAI values in coeval rocks increase downward through the stack of allochthons; (4) the same CAI values in rocks above and below the Ellesmerian unconformity in the northeast Brooks Range; (5) an association of anomalously high CAI values with mineralized areas and plutonic rocks; and (6) a few anomalously high CAI areas of unknown origin that deserve geologic attention.

CAI mapping of northern Alaska shows that Cambrian through Devonian rocks in the geologically complex area of the western Seward Peninsula, along the northernmost edge of the western and central Brooks Range, and a very small area around the Yukon River at the Canadian border have thermal potential for hydrocarbons. In nearly all these areas, however, most of these rocks are beyond the thermal limit for oil. Areas that have thermal potential for both oil and gas in Mississippian through Triassic rocks include the subsurface of the north flank of the Colville basin, a 50-km-wide belt along the north flank of the Brooks Range as far east as the Philip Smith Mountains, and a small area around the Yukon River at the Canadian border.

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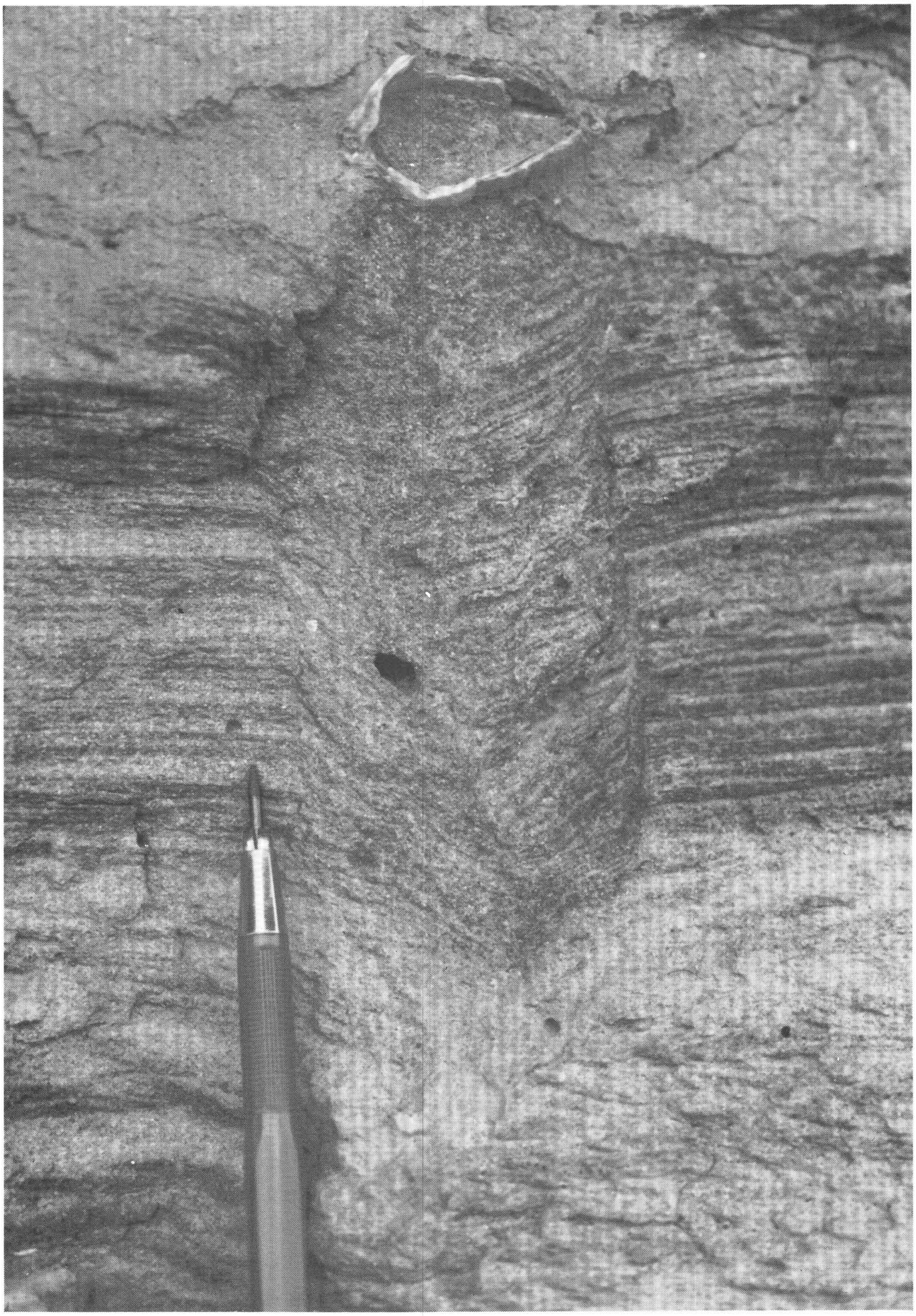
THERMAL MATURITY MODELING AND GEOCHEMICAL CHARACTERIZATION OF HYDROCARBON SOURCE ROCKS, OILS, AND NATURAL GASES OF THE ANADARKO BASIN

J. R. Hatch, D. D. Rice, R. C. Burruss, J. W. Schmoker, and J. L. Clayton

We report initial results of a study of the time-temperature history, hydrocarbon-source-rock characteristics, and geochemistry of oils and natural gases of the Anadarko basin. Despite the complex structural history of the basin, published measurements of vitrinite reflectance (R_o in percent) in the central basin indicate a reasonable



Paleoecology of freshwater mollusks augments sedimentology for interpretation of alluvial-lacustrine environments. For example, high sedimentation rates associated with crevasse splays may be reflected by bivalve escape structures. Photograph illustrates unsuccessful attempt of a freshwater bivalve (*Plesielliptio* sp.) to reach sediment-water interface by burrowing upward following rapid aggradation of sand during crevassing. Tongue River Member of Fort Union Formation (Paleocene), Powder River Basin, Montana. Photograph by J. H. Hanley, 1975.

correlation between thermal maturity and present burial depth, z (feet): $R_o=0.32e^{z/9580}$. When related to vitrinite reflectance, Lopatin's time-temperature calculations (TTI) provide a useful predictive model for thermal maturity patterns throughout the basin both now and in the geologic past. The empirically calibrated equation specific to the Anadarko basin is: $R_o=0.30(\mathrm{TTI})^{0.21}$. For a given TTI, this equation results in a lower R_o than predicted using Waples' 1980 calibration, which was based on the average of many basins.

Results of organic carbon and Rock-Eval analyses of potential hydrocarbon source rocks reveal large variation in richness and preserved organic matter type. The Middle Ordovician Simpson Group and Upper Ordovician Sylvan Shale are in general organic lean (<1 percent total organic carbon, TOC) and have limited or poor hydrocarbon-source-rock potential. The Upper Devonian–Lower Mississippian Woodford Shale is organic rich (1–14 percent TOC) with two distinct organic matter facies. Woodford Shale in the southern, southeastern, and eastern parts of the Anadarko basin contains type II (oil prone) organic matter compared to type III (gas prone) organic matter in the northern and western areas. Pennsylvanian shales with 1–5 percent TOC contain type III organic matter, whereas most Middle and Upper Pennsylvanian shale intervals (such as Stark Shale) with higher amounts of organic matter (6–18 percent TOC) contain type II organic matter.

With increasing depth (11,860–21,610 ft) in the central basin, thermogenic natural gases in Pennsylvanian sandstone reservoirs are isotopically heavier and chemically drier ($\delta^{13}C_1$ (methane): –49.2 to –33.2 ‰, $\delta^{13}C_2$ (ethane): –38.3 to –30.7 ‰, δD_1 (methane): –162 to –131 ‰, and C_1/C_{1-4}: 0.74 to 0.99). Deviations from this trend are believed due to mixing of gases generated from different source rocks at different levels of thermal maturity. In contrast, thermogenic gases produced from 1,735 to 6,685 ft in the giant Hugoton field on the northwest flank of the basin show little isotopic and chemical variation ($\delta^{13}C_1$: –44 to –42‰, $\delta^{13}C_2$: –34.3 to –32.2 ‰, δD_1: –169 to –154‰, C_1/C_{1-4}: 0.69 to 0.84). These gases are believed to have been generated at lower levels of thermal maturity than those in the central basin.

Chromatographic analysis of 24 whole oils from depths of 5,145–16,360 ft in the central basin reveals three general oil types. Type 1 occurs in Ordovician reservoirs, has pronounced odd carbon preference in the C_{11}–C_{19} n-alkanes, and very low abundance of isoprenoids. Type 2 is found in Devonian and Mississippian reservoirs, shows no odd carbon preference, and has n-alkanes as the most abundant components in the gasoline range (C_4–C_7). Type 3 occurs in Pennsylvanian reservoirs and is generally similar to type 2, but differs in having methyl cyclohexane (MCH) always greater than heptane (n-C_7), with MCH/n-C_7 up to ≈2. Intermediate oil compositions are consistent with mixing of oil types, especially between types 1 and 2, and types 2 and 3. Some multi-reservoir fields, however, show stratigraphically distinct oil types demonstrating lack of fluid communication during oil migration. In the northernmost shelf areas of western Kansas and southwestern Nebraska, geochemically similar, type 2 oils occur in Cambrian and Ordovician through Upper Pennsylvanian reservoirs. These oils correlate with extracts of the Woodford Shale from depths greater than 6,000 ft in the central Anadarko basin, implying oil migration of as much as 350–400 miles.

A NEW APPROACH TO ORGANIC GEOCHEMICAL STUDIES OF THE COALIFICATION PROCESS—CHEMICAL AND PHYSICAL EVOLUTION OF COALIFIED LOGS AS A FUNCTION OF RANK

Patrick G. Hatcher

Traditional studies of coalification have focused on the chemical evolution of coal without considering its heterogeneous chemical composition. My study devoted specific attention to one of the major components of coal, that derived from woody tissue. It is only by study of individual, genetically related components in coal of various ranks that we can gain a better understanding of the process which transforms cellular, woody plants buried in peat to structureless vitrinite in coal. Woody tissue and coalified woody tissue collected from a variety of depositional associations including peat, coal, sandstones, and shales have been studied with diverse organic geochemical and microscopic methods to ascertain the changes in chemical and physical composition brought on by the coalification process. The methods used include pyrolysis/gas chromatography/mass spectrometry and solid-state ^{13}C nuclear magnetic resonance spectroscopy (NMR). The NMR studies include use of the new dipolar dephasing method, which enhances signals for nonprotonated carbons and allows more detailed organic chemical structural analysis than is available from the conventional solid-state ^{13}C NMR method.

These sophisticated analytical tools for organic structural analysis have provided some new insights into the overall process of coalification. Woody tissue, when buried in peat, is transformed microbiologically by degradation and removal of labile organic substances such as carbohydrates, with selective preservation of lignin-like substances. This early diagenetic transformation can occur with little or no loss of cellular morphology. In contrast to traditional views, the lignin-like substances survive early diagenesis in a relatively unaltered state without transformation to soluble humic acids.

As coalification progresses to a rank equivalent to lignite, the lignin-like material is significantly altered chemically, but the woody tissue retains its cellular morphology. That cellular morphology is retained is evidence that the alteration does not involve a soluble humic acid intermediate (which some believe condenses to an insoluble gel). Rather, the lignin macromolecules are chemically altered directly as solids, and any soluble humic acid-like material appears to be a by-product of this alteration. These oxygen-rich humic substances can be mobilized from the coal during compaction and dewatering. In the process, the residual insoluble material may become depleted of oxygen, which would explain the observed loss of oxygen from coal as rank increases from lignite to bituminous coal. The dipolar dephasing NMR data show that loss of oxygen is coupled to an increase in the number of protonated carbons, also consistent with the above hypothesis.

Physical changes in coalified woody tissue occur independently of the organic chemical changes, except in samples having a finite amount of cellulose still present. This suggests that a certain degree of chemical uniformity must exist before cellular morphology degrades and the remnant cell walls coalesce to form structureless vitrinite. Once chemical homogeneity is achieved, coalescence becomes more a function of compactional pressure than of chemical changes.

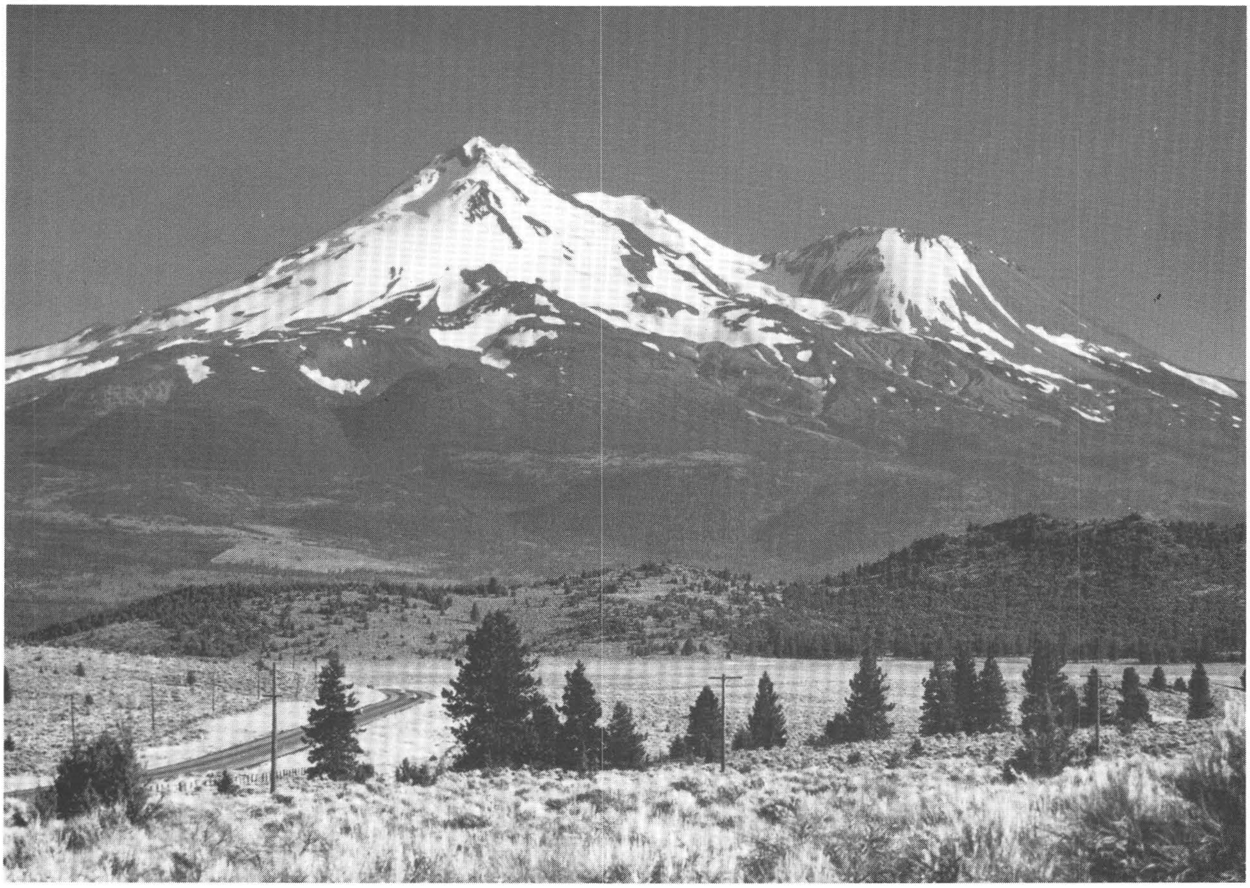
As coalified woody tissue undergoes further transformation at ranks greater than that of bituminous coal, its organic chemical composition is radically altered, primarily by loss of aliphatic structures. The dipolar dephasing data suggest that condensation of aromatic rings occurs at this stage, consistent with the traditional views about coalification at high rank.

SULFUR HEXAFLUORIDE GAS AS A STABLE TRACER OF GEOLOGICAL AND GEOCHEMICAL PROCESSES—APPLICATION TO THE ENERGY INDUSTRY AND EARTH SCIENCES

J. R. Herring and G. M. Reimer

The use of sulfur hexafluoride (SF_6) as a stable, gaseous tracer is common in the atmospheric sciences, but it is applicable to the earth science and energy industries as well. The SF_6 technique is rapid, inexpensive, and extremely accurate and precise at very low concentration levels in air. Few other tracer techniques offer its many advantages: ease of detection, self-contained, suitcase-size, field-portable instrumentation for about $5,000 (1985), and data acquisition and analysis in real time on site. Of consequence to releases of the tracer into the environment and stability of the tracer, the gas is both chemically stable and nontoxic. The natural background of SF_6 in air is low, about 1 part per trillion, which eliminates annoying or interfering background signals. Most important, the detection limit of the instrument is a sensitive few parts per trillion (for example, a standard cylinder of gas, about 6 m^3 at STP, diluted into a cube of air 18 km on edge). This allows extremely detailed tracer studies to be performed.

As an example of geologic application of this technique, we have used the tracer to define the structure and extent of an abandoned, underground, burning coal mine. This particular study is directly relevant to studies in geologic hazards and mining, as well as relevant to geologic engineering. The interest in determining the extent of this mine lies in providing new information on the combined hazards from fire and possible subsidence at the abandoned workings. We have enhanced the tracer technique by combining sulfur hexafluoride with helium, taking advantage of the differences in diffusion properties between the two gases. Specifically, our study sought to define (1) the extent of the abandoned mine workings, (2) diffusion rates of helium and sulfur hexafluoride through the partially collapsed mine, and



Mount Shasta, California, from the north. Photograph by Lyn Topinka, David A. Johnston Cascades Volcano Observatory, Vancouver, Wash., July 1984.

(3) extent of intercommunication throughout the mine, to assess the possible spread of the fire.

Our results show that we have been able to define the extent of mine workings, to obtain some idea of where the workings are flooded, and to model the diffusion of the two gases through the mine workings. As expected, eddy diffusion greatly dominates molecular diffusion in the dispersion of gases throughout the workings. Finally, we have determined that much of the mine remains connected, not only throughout its own extent but also to other, adjacent mines. Therefore, should the mine fire continue to burn, it is capable of spreading throughout much of the rest of the mine not on fire and to other neighboring mines as well.

The mine study is simply one example of the use of this tracer technique. Other potential geologic applications include tracing underground structure, determining extent of communication between underground locations, and measuring rock permeability and porosity as well as large-cavity volume. In addition, fracture zones and zones of increased permeability can be delineated with the gas.

GROUND-WATER COMPOSITION AS AN INDICATOR OF SODIUM CONTENT IN COAL IN THE POWDER RIVER BASIN, SOUTHEASTERN MONTANA AND NORTHEASTERN WYOMING

Ricky T. Hildebrand

Deposits of subbituminous coal in the Tongue River Member of the Fort Union Formation (Paleocene) often attain thicknesses of more than 30 m (100 ft) and lie within 150 m (500 ft) of the surface. This coal usually has low ash and sulfur contents, but often contains high concentrations

Anticline-syncline pair in Ordovician Viola Limestone, showing compressive deformation in area of Southwest Davis oil field along southeastern margin of Anadarko basin. Original color slide by W. J. Perry, April 1985.

of sodium. High sodium is an undesirable impurity that contributes to ash fouling in coal-fired boilers, and much research has been devoted to methods of mechanically or chemically reducing the sodium content of low-rank coal.

The coal deposits of the Tongue River Member are major aquifers in the Powder River Basin. The coal saturated by ground water is a dynamic hydrogeochemical system in which the concentrations of major cations and anion complexes tend toward chemical equilibrium. Adsorbed sodium, for example, enters into the following cation-exchange equilibrium reaction with calcium ions in solution under standard chemical conditions (STP): $2Na^{+}(ad) + Ca^{2+} \rightleftharpoons Ca^{2+}(ad) + 2Na^{+}$. The direction in which this reaction will proceed depends on the relative concentrations of the ions and the adsorption affinity of the substrate.

To investigate the chemical processes controlling the sodium content of coal, I compared concentrations of calcium, magnesium, and sodium in coal and ground-water samples from stratigraphically equivalent coal deposits. The results suggest that the sodium content in coal depends on the relative concentrations of the divalent calcium and magnesium cations and of monovalent sodium cations in solution. These cation concentrations, which define the sodium adsorption ratio (SAR), control cation-exchange reactions between ground water and the functional groups in the coal. In general, the SAR for ground water is inversely proportional to the calcium content of the coal; a high SAR indicates a high sodium content. Large amounts of sulfate in ground water increase the availability of exchangeable sodium relative to calcium and magnesium without altering the concentrations of these cations.

Ion exchange, governed by the ion concentrations in ground water, is the primary mechanism controlling the sodium content of coal deposits in the Powder River Basin. Chemical data obtained from carefully collected and properly analyzed water samples from coal beds may eventually be used to predict the ash-fouling properties of the coal before mining.

SEQUENTIAL TECTONICS OF THE WESTERN MARGIN OF THE POWDER RIVER BASIN, JOHNSON AND SHERIDAN COUNTIES, WYOMING

E. Neal Hinrichs

Recurrent movement on northeast-trending faults in the eastern Bighorn Mountains has offset mafic dikes of Archean age and thrust faults in Tertiary rocks of the western Powder River Basin. The largest component of movement on these faults is strike slip, which has accentuated the Piney lobe and offset the Clear Creek thrust fault.

Sedimentary rocks exposed on the western edge of the asymmetric Powder River Basin total about 5,180 meters in thickness and range in age from the Middle Cambrian Flathead Sandstone to the Eocene Wasatch Formation. Archean basement rocks are igneous and metamorphic, mainly gneiss, granite, and dikes and plugs of diabase, basalt, diorite, and pyroxenite.

The largest structure in the area is a concealed high-angle reverse fault which was detected by seismic methods and reported by N. H. Foster, P. E. Goodwin, and R. E. Fisher in 1969. The fault, named the Buffalo Deep fault by D. L. Blackstone Jr., in a 1981 study, dips westward and has an estimated throw of 400 meters. Offset on this fault reaches to the top of the Fort Union Formation, but not into the Wasatch Formation. Other structures, moderately well to well exposed, have been investigated by many geologists, the first of whom was probably G. H. Eldridge, who in 1894 grouped the faults and folds into three blocks—northern, central, and southern. The northern and southern blocks show similar structures produced by compression from the northeast, namely asymmetric folds with steep southwest limbs and reverse faults that dip northeast. In contrast, the central block contains thrust faults and high-angle reverse faults that dip southwest. My detailed mapping in the central block shows the following sequence of deformation: (1) normal faulting with a dominant northeast trend followed by intrusion of mafic dikes during Late Archean time; (2) uplift of the Bighorn Mountains and high-angle reverse faulting of tilted Paleozoic and Mesozoic rocks during the Laramide orogeny; (3) thrust faulting during late Eocene; (4) strike-slip faulting, post-Eocene, with some recurrent movement on Precambrian fault zones; (5) normal faulting mainly along traces of thrust faults, basin side down.

The economic importance of this tectonism bears directly on the search for buried thick deposits of coal and accumulations of oil and gas. The lack of sizeable coal deposits in the Fort Union Formation north of Crazy Woman Creek, mentioned by R. K. Hose, can be explained in part by differential uplift of the central block. This uplift diverted streams and shifted the peat swamps. The search for oil and gas has progressed to testing unconventional traps, such as granite overthrusts, as in the Granite Ridge hole drilled by the Gulf Oil Company on the Piney lobe. Although this was a dry hole, it proved the low angle of the thrust fault. The well being drilled (1985) by Arco on the upper plate of the Clear Creek thrust may penetrate producing zones in the sediments beneath the granite.

THREE STATISTICAL METHODS FOR ESTIMATING UNDISCOVERED RESOURCES BASED ON THE MINNELUSA PLAY, POWDER RIVER BASIN

J. Houghton, E. Attanasi, G. Dolton, L. Drew, R. Mast, D. Root, and J. Schuenemeyer

The Minnelusa play is used as a case study for three approaches to oil and gas resource estimation. The play, on the broad east flank of the Powder River Basin, Wyoming, includes about 150 oil fields in a suite of primarily stratigraphic traps, controlled by a regional unconformity and a regional seal. Trap morphology and size are controlled by paleotopography, reservoir truncation, internal formational variations resulting from depositional or diagenetic factors, and small structures with stratigraphic overtones.

Geographic limits to the play are uncertain; however, industry exploration has defined a concentration of pools on the central east flank of the basin, with only a scattering outside that flank. A question remains whether the spatial distribution of discoveries to 1985 is caused by geologic or economic factors. The drilling data and field file were developed and modified extensively from the Well History Control System (WHCS), PDS (Petroleum Data System) data, and published information.

Each estimation technique relies on a different type of information and is adapted to a different scale. The first estimation technique is based on determining the area of interest to explorationists. The prospective area can be calculated from the drilling record, as an alternative to detailed geologic data, in basins where some exploration already has been done. The prospective area in the Minnelusa play is divided into two equal halves, early and late. These areas were delineated on the basis of the sequence of wildcat drilling in many diverse tracts. The first half, delineated prior to 1966, has accounted for 90 percent of the oil discovered and for 72 percent of the wells drilled. Extrapolation of the discovery rate in the first half indicates that the basin will produce ultimately 394 million barrels of oil. The average discovery rate for the second half has been only 19 percent of the discovery rate of the same number of wells in the first half. From these data and calculations, it is inferred that the ultimate production of the second half will be only 75 million barrels and that the ultimate production from both halves of the delineated area will be 469 million barrels, of which 381 million barrels have already been discovered. It appears, however, from analysis based on extrapolating the growth of the productive area as a function of the number of cumulative exploratory wells, that the undiscovered oil resources in the play are smaller than the previous inference.

The second class of techniques is based on discovery process models, which were used to predict the expected volume of petroleum to be found by future wildcat wells. These models include the negative exponential extrapolation presented by Arps and Roberts (A-R) and two relatively newer models by Meisner and Demirmen (M-D) and Hinde and Forman (H-F). The M-D and H-F models assume that the size distribution of fields is lognormal and that the probability of finding a field is proportional to a discoverability coefficient estimated from past drilling and discoveries.

Forecasts made by H-F and M-D are sensitive to the underlying equations describing probability of success and tend to give larger estimates than A-R, at least when the model of success probability is modified to better fit the empirical record. Although H-F and M-D offer advantages, such as avoiding the problems associated with an arbitrary choice of class size and yield estimates, the unit of exploratory effort needs to be determined exogenously and there is no prediction of the ultimate underlying field size distribution. None of these methods yields a forecast of more than 55 million barrels of oil to be discovered in the play with the drilling of twice as many wildcat wells as have been drilled already in the play.

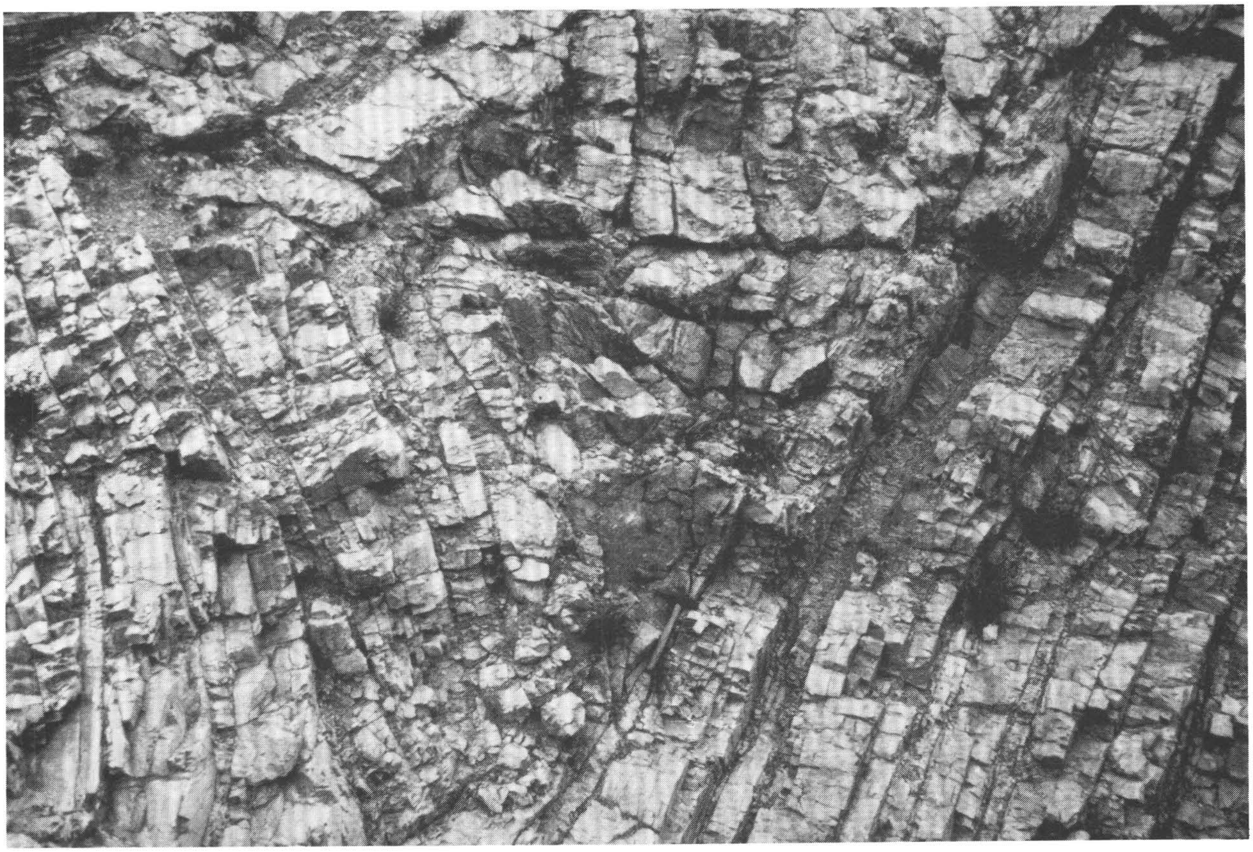
A third method, which also uses the Minnelusa data, assists resource estimation in other areas. This technique uses less detailed data than a drilling record and relies more on geologic data and comparisons with mature analog regions. In this case, however, the larger fields in the Minnelusa play are used as a statistical analog for other plays. The Minnelusa field file contains 152 fields, of which 68 are larger than 1 million barrels. When fit by the Shifted Pareto (SP), a modification of the Pareto Distribution, the largest field is expected to be 55.6 million barrels, almost exactly the 51.7 actually discovered, and the rest of the sample fits almost as well. The fitted curve has a thick right-hand tail—the population coefficient of skew is infinite. The total amount of oil in the 68 fields, 377 million barrels, is matched exactly.

Based on geologic analogs and estimates of either the total amount of oil and gas or the size of the largest field, field size distributions from the Minnelusa and other already-explored regions can be used to describe the likely properties of the field size distribution in a region being assessed. This SP distribution allows an estimate of the expected size of each field, ordered by size; the amount of oil that would be reduced from the estimate by limiting the size of the largest predicted field; and those field sizes smaller than the current economic cutoff.

TERRANES, RESOURCES, AND THE GEODYNAMICS OF CONTINENTAL GROWTH

David G. Howell and David L. Jones

Continents increase in mass because of the addition of new material (primarily fragments of volcanic islands, seamounts, and hydrogenous and biologic sediments) formed in oceanic settings. Admixed with these are continental fragments and piles of terrigenous sediment; both of these affect continental recycling but not net growth.



Ordovician Viola Limestone in rotated ramp anticline on north flank of Arbuckle anticline, on east-facing cut, Interstate Highway 35. Original color slide by W. J. Perry, April 1985.

Terranes are the fault-bounded fragments of these materials found in orogenic belts. In the Circum-Pacific region, the rate of accretion since the breakup of Pangaea in early Mesozoic time is calculated as 2 to 2.5 km^3/yr, or as much as 80 m^3/s. An average global growth rate needed to account for the entire mass of continents (7.6×10^9 km^3) since Early Archean time (3.8×10^9 yr) is 2.0 km^3/yr; the flux of continental growth, however, remains a topic of great controversy.

Although ocean crust contributes little to the mass of continents, the creation of ocean crust creates the "conveyor belt" that leads to the formation of sialic material; in addition the conveyor belt leads to the accretion and dispersive kinematics that result in the growth and shaping of continents. The isochrons deduced from magnetic stripes in the modern oceans (about 300×10^6 km^2 in area) indicate an average age for ocean crust of only 70 m.y. Oceanic crustal rocks form at a rate of 800 m^3/s assuming a 6-km-thick crust. If plate tectonic processes have been operative since 3.8 Ga, even at modern rates as many as 27 world-ocean crusts would have been born at spreading centers and lost back to the mantle in subduction zones.

The processes linking tectonics, sedimentation, and resources are not clearly understood, but as we learn more about the geologic and physical properties of terranes, as well as their kinematics and dynamic histories, our prospecting perspicacity should improve. Some explanations are already available: Campeche, the Persian Gulf, and Prudhoe Bay are all passive margin sequences tectonically overrun by foreland thrust and fold environs; southern California and the North Sea represent dispersive settings, transcurrent and orthogonal rifting, respectively. What other as yet untested conditions could house petroleum accumulations, for example, deep source gas in accretion piles associated with the subduction of sediment, or hydrocarbons locked in compressed flysch basins that are overridden by exotic terranes, ... ?

EVALUATING COMPOSITIONAL TRENDS IN MIOCENE-PLIOCENE STRATA OF SOUTH-CENTRAL COASTAL CALIFORNIA

Caroline M. Isaacs, Kathleen C. Stewart, and Larry L. Jackson

The Miocene Monterey Formation is the most prolific petroleum-source rock in California and locally an important petroleum-reservoir rock. Because of recent giant petroleum discoveries in fractured Miocene strata of offshore California, regional facies models of these strata are important to petroleum exploration and production. Of particular interest are the distributions of organic matter (which is the petroleum source), clay (which critically reduces fracturability and hence reservoir potential), and diagenetic silica and dolomite (both of which enhance fracturability). Our results suggest that quantitative determination of sedimentary components by chemical analysis of cuttings may prove valuable for determining regional facies patterns and evaluating regional source and reservoir potential.

Regional synthesis of the Monterey Formation has proven to be difficult because Monterey strata are mainly uncommon, fine-grained biogenic lithotypes, Monterey depositional facies patterns are poorly understood, diagenetic patterns are unlike those in more widely studied sedimentary rocks, and well-log responses do not follow accepted interpretive rules. In the south-central coastal basins (Santa Maria, Santa Barbara-Ventura, Huasna), another major difficulty in evaluation of the Monterey Formation is lithologic heterogeneity. Although Monterey strata in this area are mainly fine grained, lithotypes vary markedly on scales ranging from tenths of an inch (centimeter) to tens of feet (several meters). In terms of sedimentary composition, individual beds are widely scattered over the ranges 2–95 percent biogenically derived silica, 0–95 percent carbonate minerals, 5–80 percent terrigenous detritus, 0–25 percent apatite, and 1–35 percent organic matter. Because the entire range of compositions is present in many stratigraphic intervals as thin as 6 ft (2 m), the number of samples needed to determine a representative value is almost prohibitive. Thus identification of compositional trends through time (even in single sequences) is extremely difficult, and comparisons between sequences have been virtual guesswork.

We have approached the problem of lithologic heterogeneity by chemical analysis of bulk cuttings samples, studying four wells as follows: (1) Hondo offshore oil field, Santa Barbara Channel (two wells); (2) Orcutt oil field, onshore Santa Maria basin; and (3) the Point Conception Deep Stratigraphic Test well (OCS-Cal 78–164 No. 1), "offshore Santa Maria basin." For each well, we evaluated Miocene and Pliocene strata ranging in thickness from 2,800 ft (850 m) to 7,000 ft (2,150 m), by analyzing cuttings samples representing interval-averages of between 10 and 30 ft (3 and 10 m) of strata.

Particularly important in evaluating the cuttings method is the Union Hobbs 22 well in the Orcutt field, where results can be compared with analyses of individual core samples from the nearby Union Newlove 51 well. In the uppermost Miocene and Pliocene Sisquoc Formation overlying the Monterey Formation, sedimentary component abundances are relatively uniform throughout a 1,000-ft (300-m) interval, and values based on eighteen 10-ft (3-m) interval averages (av detritus 66 percent, av silica 28 percent) are closely representative of values based on 12 core samples (av detritus 68 percent, av silica 27 percent). Also of importance in evaluating the method are results from 5,000 ft (1,550 m) of Miocene and Pliocene strata in the two wells in the Hondo area; the striking similarity of the compositional sequence confirms that cuttings analysis provides an excellent basis for detailed correlation. Our results thus indicate that quantitative analysis of cuttings provides representative compositional data which can identify major compositional trends, and the method should prove valuable for determining regional facies patterns and evaluating regional source and reservoir potential.

GEOMETRY AND HYDROCARBON APPRAISAL OF THE PUTNAM THRUST ADJACENT TO THE SNAKE RIVER PLAIN NEAR BLACKFOOT, IDAHO

Karl S. Kellogg, Frank R. Hladky[3], and George A. Desborough

Late Tertiary basin-and-range extensional faulting about 10–20 km southeast of Blackfoot, Idaho, has broken the Putnam thrust to produce a com-

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plex fault geometry. The Putnam thrust is considered to be the northern extension of the Upper Jurassic to Cretaceous Paris-Willard thrust system and plunges beneath upper Tertiary and Quaternary volcanic and sedimentary deposits of the Snake River Plain.

Our studies, which extend previous work by D. E. Trimble of the U.S. Geological Survey, show that

1. Strata from both the lower and upper plates of the Putnam thrust are gently to tightly folded and commonly overturned;
2. Fault blocks are rotated as much as 60°, predominantly to the east, during late Tertiary extensional faulting probably younger than 10 Ma, as shown by attitudes on tuff, conglomerate, and limestone of the upper Tertiary Starlight Formation;
3. The upper plate of the Putnam thrust in the Yandell Springs 7½-minute quadrangle includes strata as old as the Middle to Late Cambrian Nounan Limestone and as young as the Silurian Laketown Dolomite (both units previously unrecognized in the study area);
4. Lower plate strata include the Upper Mississippian Monroe Canyon Limestone, the Lower Pennsylvanian to Lower Permian Wells Formation, the Permian Phosphoria Formation, and the Lower Triassic Dinwoody and Thaynes Formations;
5. A window through the Putnam thrust is extensively broken by normal faulting, exposing lower plate rocks of the Wells, Phosphoria, and Thaynes Formations;
6. Hydrothermal fluids, probably associated with volcanic activity along the Snake River Plain, have dolomitized many of the limestone units (notably from the Nounan and Lower Ordovician Garden City Formations) during the Tertiary; and
7. As noted by Trimble, normal faulting extensively brecciated rocks of the upper plate of the Putnam thrust, particularly the Upper Ordovician Fish Haven Dolomite.

The Meade Peak Member of the Phosphoria Formation is known to be a highly favorable hydrocarbon source rock in the Idaho-Wyoming thrust belt. At the Gay phosphate mine, in the eastern part of the study area, these strata are slightly beyond mature, rather than supermature (metamorphosed), as previously reported. The potential exists, therefore, for hydrocarbon generation after thrusting in this region.

ALLOCYCLIC CONTROLS ON THICK COAL DEPOSITION IN SEDIMENTARY BASINS—SOME POWDER RIVER BASIN EXAMPLES

Bion H. Kent, Frances Wahl Pierce, Carol L. Molnia, and Edward A. Johnson

Sedimentary basins form by subsidence and are filled by sediments eroded from opposing, uplifted source areas; many coal basins were tectonically active when coal-bearing rocks were deposited. The repeated episodes of tectonic subsidence and uplift that induced changes in climate, ground water, and base level also introduced fluctuations in energy of distributary systems for sediment infill: high-energy episodes of clastic influx were interspersed with quiescent, low-energy periods of peat accumulation, causing basin rock-types to be repeated vertically in crude cyclic sequences. These allocyclic controls interacted to establish and prolong optimal environments and conditions necessary for thick peat to accumulate, to bury and preserve the peat beds beneath sediment cover, and to increase depths of burial and sediment overburden. The nature of such control is best described by a "teeter-board" hypothesis based on a simple assumption: if one area is subsiding while an opposing area is uplifted, a "fulcrum" area in between is in dynamic equilibrium.

The Powder River Basin, Montana and Wyoming, is a product of Laramide structural movements. Some of the largest coal deposits in the world are in Tertiary rocks along the eastern flank of the basin. During middle Paleocene to Eocene time, high-energy clastic influx from eastern, uplifted source areas alternated with low-energy periods of thick peat accumulation. Pivotal effects of western (basin) subsidence and eastern (Black Hills) uplifts produced linear fulcrum areas in dynamic equilibrium, elongate north-south across the west-tilted paleoslopes that formed the eastern flank of the developing basin. During quiescent periods, when subsidence and uplift were subdued and sediment infill was minimal, the linear fulcrum areas became broad centers for peat accumulation. Fulcrum areas (centers for peat accumulation) were shifted west by eastern uplifts and east by western subsidence. Several fulcrum-area migrations occurred in response to subsidence and uplift over a prolonged period. The overall migratory shift was westward, ahead of the succeeding episode of clastic influx that buried the peat beds.

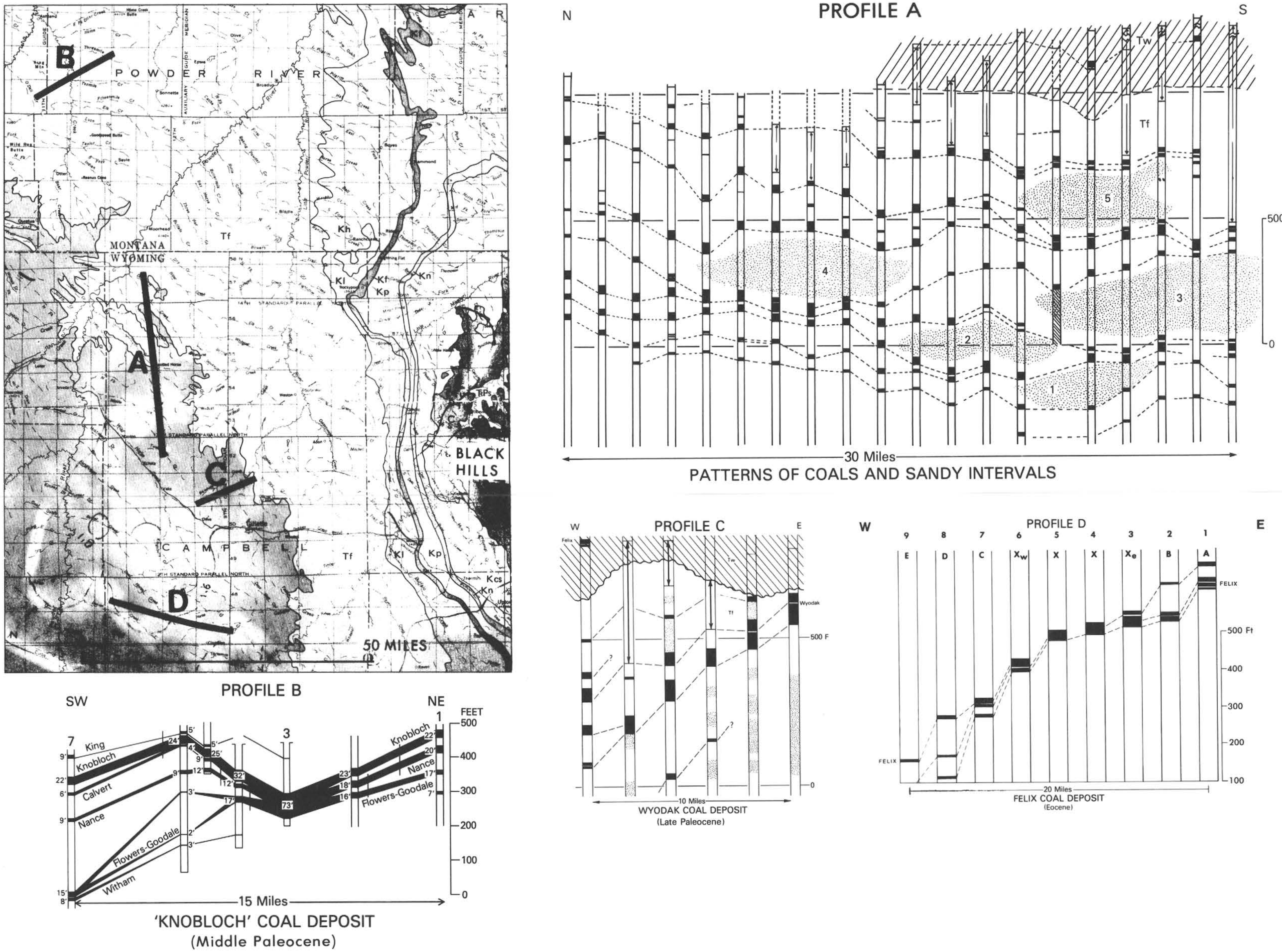


FIGURE 1.—Profiles, chronology, and features of thick coal deposition in Paleocene and Eocene rocks along the eastern flank of the Powder River Basin, Montana and Wyoming. Tf, Fort Union Formation (Paleocene); Tw, Wasatch Formation (Eocene).

Figure 1 illustrates chronology and characteristics of thick coal deposits in Paleocene and Eocene rocks along the eastern flank of the Powder River Basin. Profile A (fig. 1), of upper Paleocene coals and sandy intervals, is oriented north-south approximately parallel to the depositional strike; the profile illustrates how quiescent periods of thick coal deposition were interspersed with high-energy episodes (labeled 1, 2, 3, 4 and 5) of sediment infill from eastern source areas. Successive episodes of clastic deposition exhibit the familiar offset-stacking pattern that characterizes fluvial architecture. Laterally continuous coal beds separate those sandy intervals (see profile A, fig. 1). The east-west profiles (B, C, and D, fig. 1) illustrate some characteristics of thick coal deposits. Closely associated coal beds merge locally to form single beds of combined coal and the thickest single bed of combined coal forms the central core of the deposit. The central cores of the "Knobloch" (profile B) and Felix (profile D) coal deposits split eastward to thin upper benches and thick lower benches, and westward to thick upper benches and thin lower benches, suggesting fulcrum-area migration and overall migratory shift westward. As indicated on profile C (fig. 1), upper Paleocene rocks containing the Wyodak coal deposit were uplifted, tilted westward, and beveled to the central core of the deposit prior to the advent of Eocene sediment cover; consequently, an unconformity separates Paleocene rocks from Eocene rocks and only the western half of the Wyodak coal deposit is preserved in the rock record.

In the Powder River Basin examples, the geometries of thick coal deposits illustrate allocyclic controls and provide a model for analogs in ancient and modern settings.

CONTINENTAL MARGIN MAPPING PROJECT, UNITED STATES ATLANTIC MARGIN—A SYNTHESIS OF GEOLOGIC AND GEOPHYSICAL DATA AND INTERPRETATIONS

Kim D. Klitgord and Gary H. Hill

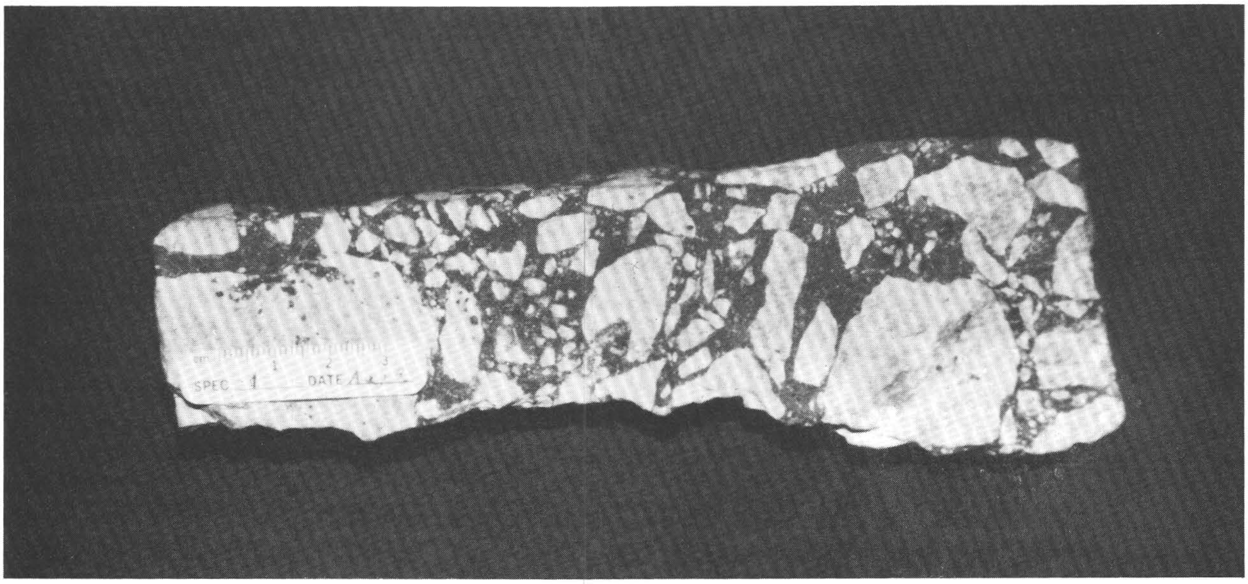
Syntheses of geologic and geophysical studies on the United States Atlantic continental margin are being compiled in a series of maps and a digital database. Both map and digital forms are being used to facilitate the transfer and use of the extensive information acquired by the U.S. Geological Survey on the United States continental margins. For this project, the Atlantic margin has been divided into four regions: Georges Bank basin and Gulf of Maine, Baltimore Canyon trough, Carolina trough, and Blake Plateau basin. Each region extends from the seaward edge of the U.S. Exclusive Economic Zone to the Coastal Plain onlap (Fall Line) onshore. Primary data sets for this series have been derived from multichannel seismic-reflection profiles, magnetic surveys, and gravity surveys as well as drill hole and bottom sample data.

Mapping is being done on an Albers Conic Equal Area Projection using standard parallels of lat 29.5° N. and 45.5° N., at a scale of 1:1 million, and will be compatible with the National Atlas geologic map and tectonic map of the United States. Individual maps in the series comprise topography and bathymetry, tectonic features, isopachs of various sedimentary units, depth contours of basement and various sedimentary surfaces, paleoenvironment, magnetic-anomaly contours, and gravity-anomaly contours, as well as drill-well locations, seismic-line navigation, and offshore leases.

THERMAL EVOLUTION OF KEROGEN AND PHYTOCLASTS IN THE EASTERN UNITED STATES EARLY MESOZOIC BASINS AS A GUIDE TO MATURATION

R. K. Kotra, R. M. Gottfried, E. C. Spiker, P. G. Hatcher, and A. J. Froelich

Kerogen and phytoclasts (coalified plant fragments) from the sedimentary rocks in exposed early Mesozoic basins of the Newark Supergroup in the Eastern United States are currently under study; we are using several organic geochemical techniques to discover the thermal history and sources of the organic matter in the host rocks. Solid-state C–13 nuclear magnetic resonance spectroscopy, pyrolysis-gas chromatography, stable isotope ratios. and vitrinite reflectance are being applied to compare the nature of the organic matter in phytoclasts and kerogen derived from lacustrine shales. Assessments of kerogen maturity can be influenced by the source of the parent organic matter. The rank of phytoclasts (known to be of vascular plant origin) from the same rock can provide an additional or independent measure of the degree of heating.



Uranium ore from an Arizona breccia pipe showing uraninite in matrix surrounding bleached sandstone breccia clasts. Largest clast is 5 cm in length (photo from 1985 study by K. Wenrich and J. Rasmussen).

The composition of the preserved organic matter in the samples examined so far is quite variable. The rank of phytoclasts ranges from that of subbituminous coal to that of anthracite with no relation to age or to apparent depth of burial. This implies that other factors, such as hydrothermal activity, may have played an important role during maturation. Phytoclasts recovered from zones of copper mineralization, for example, are consistently highly altered, indicating a high degree of thermal stress possibly associated with hydrothermal activity. Kerogen associated with phytoclasts, as well as kerogen from shales devoid of phytoclasts, was examined primarily to determine its source. The data showed that the composition of kerogen varies widely. Some samples showed characteristics similar to sapropelic kerogen (such as from shales in the Green River Formation); others appeared to be composed of humic kerogen derived from vascular plant remains.

These preliminary organic geochemical investigations show that the organic matter in the lacustrine strata of the Eastern United States early Mesozoic basins exhibits varying degrees of thermal maturity and has varying source compositions. Attempts to determine the oil and gas potentials of these shales must take into consideration the regional variabilities of these factors.

EXPERT SYSTEMS RESEARCH AND ITS APPLICATION TO ENERGY STUDIES

Katherine B. Krystinik

Expert Systems, or Knowledge-Based Systems, have high potential for aiding in energy research. Expert systems derive strength from the incorporation of both factual and heuristic, or "rules-of-thumb," knowledge.

Expert systems are being constructed within the U.S. Geological Survey to aid in the interpretation of depositional environments, a key component of sedimentary basin analysis and the analysis of regional geologic trends. Particular environments or several closely related depositional environments are represented by expert systems which incorporate the understanding of an expert. This work is an excellent application for expert systems techniques for several reasons: (1) a representative problem can be solved in a reasonable amount of time; (2) recognized experts exist but are often not readily accessible; (3) numerous practical applications for these systems exist.

An expert system for beach deposits, developed in conjunction with H. Edward Clifton, illustrates how depositional environments are identified. Lithofacies characteristic of a particular environment are interpreted from observed features of the outcrop or core; these features include lithology, sedimentary structures, bioturbation, and so on. The user volunteers information in response to questions asked by the system during a consultation. Uncertain responses are allowed and incorporated into the reasoning. The user is able to obtain additional information on each of the questions or the reasoning used in asking them. The dialogue varies in different consultations because the questions asked by the system depend upon the responses of the user to previous questions. At the end of the consultation, the system evaluates the likelihood that the deposit under consideration indicates a particular depositional environment. The reasoning used by the system in reaching the conclusion is accessible to the user. Appropriate references are easily added.

Systems of this sort are useful as aids in consulting and teaching as well as for documenting heuristic knowledge. The documentation facilitates comparison of several experts' models for one depositional environment as well as comparison across depositional environments. The depositional environment expert systems can serve as the basis for a more extensive system, potentially including knowledge from other geologic specialties, for example, log analysis.

FLUID MIGRATION PATHWAYS—EVIDENCE FROM THERMAL MATURITY MAPPING IN SOUTHWESTERN WYOMING

B. E. Law, M. R. Lickus, and M. J. Pawlewicz

Regional thermal maturity investigations in the Greater Green River basin of Wyoming, Colorado, and Utah, funded by the U.S. Department of Energy's Western Tight Gas Sands Program, have facilitated the identification of fluid migration pathways and provided specific information bearing on the origin of the Patrick Draw oil and gas field in southwestern Wyoming.

Vitrinite reflectance (R_m) data from Upper Cretaceous and Tertiary subsurface samples of coal and carbonaceous shale, siltstone, and sandstone in the Greater Green River basin show several areas wherein levels of organic maturation are abnormally high with respect to regional levels. One of these areas centers on the Patrick Draw field and is subparallel to a northeast-trending zone of faults. R_m values in the upper Cretaceous Almond Formation range from 0.48 percent immediately adjacent to the abnormally high area to 0.68 percent within the area. An isoreflectance line superimposed on a structural cross section extending from the southwestern part of the Green River Basin, east-northeast through the Patrick Draw field to the Rawlins uplift, shows that the dip of the isoreflectance line is generally less than, or equal to, the structural dip. However, in the vicinity of the Patrick Draw field, the dip of the isoreflectance line is greater than the structural dip, indicating that the organic matter in this area has been subjected to higher temperatures than in adjacent areas.

We believe that this and other similar areas of abnormally high levels of thermal maturity in the region occur as a result of hot fluids coming into contact with organic matter, elevating the level of thermal maturity above regional levels. In the specific example of Patrick Draw, we suggest that the hot fluids were hydrocarbon bearing, having originated from pre-Almond source rocks located in a more basin-centered position. In response to hydrocarbon generation and expulsion, hot, hydrocarbon-bearing fluids migrated to structurally higher positions along the Wamsutter arch, where faults and fractures provided vertical pathways. As the fluids flowed upward along fault and fracture surfaces, hydrocarbons entered the porous and permeable reservoirs of the Almond Formation and accumulated in stratigraphic traps. The passage of these hot fluids through the faulted and fractured rocks is indicated by abnormally high levels of organic maturation. The example of the Patrick Draw field illustrates how thermal maturity investigations can apply to problems concerning fluid migration.

AN APPLICATION OF AZIMUTHAL VERTICAL SEISMIC PROFILES

M. W. Lee

An azimuthal vertical seismic profile (VSP) is defined as seismic measurements inside a borehole from sources located in azimuthal directions relative to the borehole. One of the advantages of an azimuthal VSP is that it can identify subtle stratigraphic horizons and their spatial distribution near the well site. The VSP method is of particular importance when the surface seismogram is of poor quality, due to low seismic frequency or severe surface static and noises.

An azimuthal VSP technique has been used near Rifle, Colorado, to investigate the lateral extent of lenticular sand bodies in the Mesaverde Group. A high-resolution, three-dimensional seismic survey was conducted in this area previously, but the surface seismic data were not effective in delineating the lenticular-type sand bodies in this study area. Thus, an azimuthal VSP experiment was carried out at the U.S. Department of Energy Multi-Well Experiment site in April 1984. Two wells were profiled with a tri-axial, three-component downhole geophone and a 450 in.^{3} (7,374 cm^3) surface airgun source at four different source locations. Due to poor ground conditions, airgun malfunctions, and time limitations, the data quality was only fair.

After careful data processing, however, the seismic character of the lower coastal sand bodies could be identified. Interpretation of the spatial distribution of sand bodies was based mainly on the laterally stacked vertical component of the VSP data, in conjunction with one- and three-dimensional seismic modeling, and a geological interpretation in 1985 work of J. C. Lorenz.

Individual sand bodies were difficult to delineate due to the lack of high-frequency content of the conventional VSP data. However, the lower coastal sand bodies (Yellow and Red zones of J. C. Lorenz, 1985) could be mapped. The Red sand trends northeast with an average width of 800 ft (240 m), whereas the Yellow sand trends northwest with an average width of 600 ft (180 m). This investigation suggests that azimuthal VSP surveys can detect and delineate finite-extent bodies, such as reservoirs.

LASER MICROPROBE "FINGERPRINTING" AND ORIGIN OF ELEMENTS IN VITRITE BANDS FROM SELECTED COAL BEDS OF EASTERN UNITED STATES

Paul C. Lyons, John J. Morelli[4], David M. Hercules[4], Curtis A. Palmer, Floyd W. Brown, Janet D. Fletcher, and Marta R. Krasnow

Vitrinite is the major maceral group found in Carboniferous coal beds of Eastern United States; thus, most of the major chemical and physical properties of these coals are probably related to this microconstituent. Macerals of the vitrinite group are commonly thought to have originated from woody tissue which underwent degradation and other chemical changes before and during diagenesis. These chemical changes are assumed to have resulted in the mobilization, enrichment, and entrapment of certain elements and compounds available from the degrading peat tissue, pore fluids, and mineral matter in the peat and surrounding strata.

The distribution of elements and compounds in a suite of vitrinites was analyzed with a laser microprobe (LAMMA), supplemented by analyses by neutron activation and d.c. arc spectrographic techniques. LAMMA is a state-of-the-art mass microanalyzer capable of detecting all isotopes and elements in the parts per million range and compounds up to masses of 2,000 amu (atomic mass units). Detection limits are in the parts per billion range for certain elements such as Na, K, and F.

We selected vitrinites (generally banded telinites) from nine coal beds in Eastern United States, ranging in rank from high volatile C bituminous coal to meta-anthracite, to be analyzed by LAMMA. H/C atomic and $R_o$max reflectance data were used to generate a rank series of the vitrinites. For each coal bed, three vitrinite sites, generally within the same vitrite band and several hundred or more micrometers apart, were analyzed by LAMMA; a total of 12 analyses were averaged for each site.

Of elements analyzed, Na and Fe were detected in all vitrinite bands examined; Li, Mg, Al, Si, K, Ca, Ti, Sr, and Ba were commonly present; P, S, Se, Zr, Mn, Ga, As, Bi, Ni, Cr, Co, V, Sc, Cu, Zn, La, Ce, F, and Cl were less commonly or rarely detected by LAMMA. Pyritic sulfur is

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detected by LAMMA as S^+, Fe^+, FeS^+, $FeS_2{}^+$, Fe_2S^+, and $Fe_2S_2{}^+$. In mixtures of pyrite and macerals, most of the sulfur in pyrite is usually detected as SH, as opposed to sulfur, due to the availability of hydrogen from LAMMA micropyrolysis.

Presence of several elements detected by LAMMA was confirmed by instrumental neutron activation or spectrographic analysis of bulk vitrinite concentrates from nine samples. The following ranges in concentrations were detected by neutron activation techniques (in ppm): K (<100–650), Na (50–600), Ba (<30–106), Sr (17–89), Zn (3–24), As (0.7–12), and Cr (2–23). Iron ranged from 510 to 4,190 ppm; this large range is most likely due to pyrite impurities in the concentrates. Ni and Co (<2–10), B (<20–79), Mn (<20–40), and Ti (76–300) were determined in two concentrates by d.c. arc spectroscopy. The same technique determined Pb (34), Ge (5), V (14), and Zr (9) in one of the concentrates.

These data indicate that vitrinite in each vitrite band analyzed yielded a distinctive suite and concentration of elements. In each of two coal beds where different vitrite bands or grains were characterized by LAMMA, the same "fingerprint" was obtained. Further work is necessary to determine if the elements found within a given vitrite band (which may represent some particular plant organ, such as a petiole) originated from the original plant matter or from secondary processes before or during diagenesis.

The results of this study indicate the usefulness of LAMMA as a new microprobe technique for organic and inorganic qualitative analysis of coal. LAMMA procedures offer rapid detection and data reduction, detection of both organic and inorganic compounds, moderate to high sensitivity for all elements, and surface cleaning by preliminary laser bursts to minimize surface contamination.

AN INTEGRATED APPROACH USING THE COMPUTER IN THE GEOLOGIC ASSESSMENT OF HYDROCARBON RESOURCES OF THE POWDER RIVER BASIN, WYOMING AND MONTANA

Richard F. Mast, James E. Fox, and Gordon L. Dolton

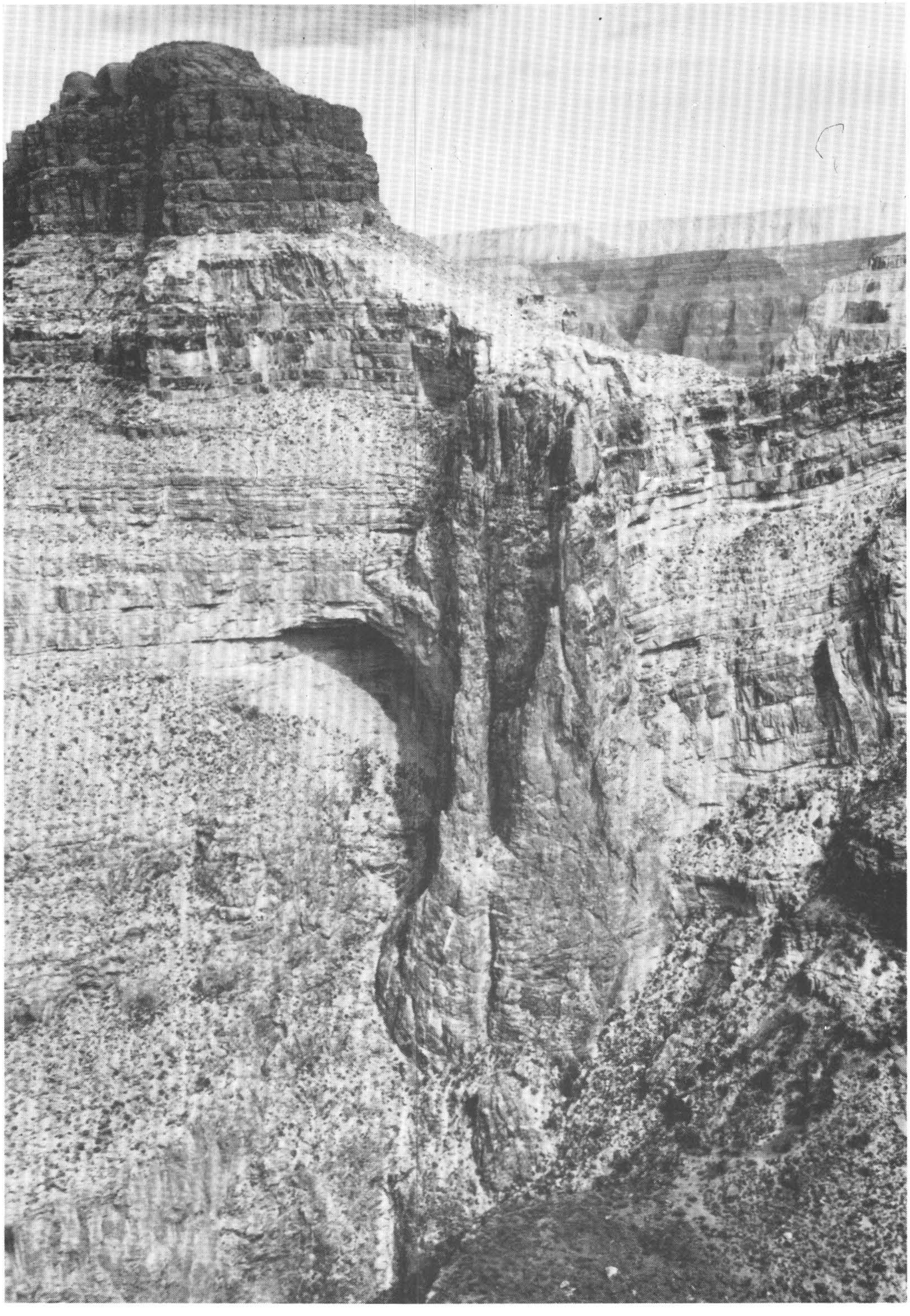
Independently created computer data files can be used together in assessing the hydrocarbon resource potential of oil and gas plays in the Powder River Basin, Wyoming and Montana. The approach we have used should be equally useful in other hydrocarbon-productive basins.

Using geologic data from approximately 200 of the deepest, strategically located oil and gas wells in the basin, we constructed a series of 20 east-west electric log cross sections. On these cross sections, formation tops, key bentonite beds, major unconformities, and stratigraphic pinchouts were identified to illustrate stratigraphic relationships of Upper Cretaceous through Pennsylvanian and, in some cases, deeper strata in the basin. We then loaded the geologic data on these cross sections into a computer file that includes well identification, location, elevation, and depth from the surface to the top of all major stratigraphic units, selected bentonite beds, and major unconformities. With this data file, the computer compiled regional isopachs of important hydrocarbon source-rock and reservoir-rock units, as well as generalized structure contours.

Geologic data files were also retrieved using all drill holes from the Well History Control System (WHCS). These WHCS data were independently verified to remove obviously spurious information from the well file and to add new information. The computer then was able to generate a series of structural contour compilations showing wildcat penetrations of several of the major oil- and gas-related units in the basin.

From the results of the geologic analysis, a series of oil and gas plays in the basin were described, geographically delineated, and their boundaries digitized to provide a framework for managing and editing stratigraphic and geographic data for use in resource assessment studies. Drill holes, oil and gas fields or pools, and oil and gas shows were then mapped for the included oil and gas plays using the data retrieved from the WHCS. Drilling statistics were compiled for the 30,000 exploration and development wells in the basin and for each of the oil and gas plays.

Finally, an example oil and gas field-data file was created for the Minnelusa play using several sources, summarizing published data for each pool. This file contains information on 142 separate pools discovered through 1981. It characterizes the geologic properties of each reservoir, and it gives size data for pools, which were in part generated or verified by extrapolating ultimate recoveries from production data. This file allows for display and analysis of such variables as



The Bat Cave breccia pipe (northern Arizona) forms a prominent 800-ft (250-m) vertical column along cliff face. Pipe is located just south of the Colorado River, principally in lower part of the Supai Group and upper part of the Redwall Limestone. Photograph by K. J. Wenrich, March 1983.

porosity, reservoir thickness, depth, and oil gravity.

Computerized data management and display systems made it possible for all of the geologic, drilling, and discovery data to be integrated and cross- checked. Integration and analysis of the geologic, drilling, and field or pool discovery data are valuable tools in the assessment of exploration maturity of oil and gas plays and the appraisal of future oil and gas resources.

GLORIA SIDESCAN-SONAR SURVEY OF THE WESTERN MISSISSIPPI FAN INTRASLOPE BASINS

B. A. McGregor, J. S. Schlee, and K. D. Klitgord

The U.S. Geological Survey has just completed a long-range sidescan survey within the U.S. Exclusive Economic Zone in the Gulf of Mexico, using the GLORIA II sidescan system of the Institute of Oceanographic Sciences of Great Britain. Portions of this survey concentrated on the slope-rise region of the central Gulf of Mexico where the Mississippi Fan laps onto the salt diapir province of the Texas-Louisiana continental slope. Numerous Pliocene-Pleistocene intraslope sedimentary basins have been formed in this area by the dynamic interaction between salt tectonics, sea-level fluctuations, and sediment-loading, as described in a 1983 study by A. H. Bouma. The shallowest of these intraslope basins are within a zone referred to as the Gulf deepwater flexure trend and are already targets for petroleum exploration. The combination of sidescan sonar imaging and seismic-reflection profiling is being used to map in detail the areal extent and distribution of these intraslope basins and to study the sedimentary deposits within the basins. Between long 89° W. and 90.5° W. the intraslope basins have received substantial terrigenous input from the Mississippi Fan system and have a morphology that resembles stepped terraces. The intraslope sedimentary basins west of about long 90.5° W. are also bathymetric basins.

Surface reflectivity of the sediment fill within the blocked-canyon intraslope basins contrasts with the reflection character of the faulted relief and bathymetric steps associated with the salt diapirs or ridges and possible collapse basins. These surficial acoustic reflectivity contrasts provide excellent imaging targets for the sidescan sonar. Variations in seismic-reflection character with depth below the sea floor are being used to map lithologic variations within the basins. Sidescan data and seismic-reflection data are being integrated into a combined study of present and past sediment deposition patterns.

TECTONICS AND THE POTENTIAL FOR HYDROCARBONS IN OFFSHORE BASINS OF WESTERN NORTH AMERICA

Hugh McLean

The enormous volumes of unexplored sedimentary rock that lie beneath and adjacent to the continental shelves of Alaska and the Pacific coast area of the lower 48 States provide an attractive target for exploration, as the United States' long-term demand for domestic hydrocarbon reserves increases. Tectonic setting strongly affects the probability of oil and gas hydrocarbon generation, migration, and entrapment in the intra-shelf and shelf-edge basins.

Basins on the Beaufort and Chukchi shelves of Alaska lie along a rifted or passive margin, and are filled with as much as 12 km of Jurassic and younger strata. On the Bering shelf, several basins formed and filled during Tertiary time in response to transtensional stress and (or) oroclinal bending between Asia and North America. Structures within the Bering shelf basins tend to be gentle low-amplitude folds related to draping over basement topography. The Aleutian Basin lies in waters deeper than 2,000 m and contains an enormous volume of sediment ponded behind the Aleutian archipelago. Along the transform portion of the basin margin, sediment thickness locally exceeds 9 km. Small basins on the crest of the Aleutian Ridge formed in response to extension and contain as much as 4 km of Neogene fill.

Shelf and slope basins of the Aleutian Ridge (which extends from the Komandorsky Islands to the Gulf of Alaska) formed in response to Tertiary plate convergence. Structures within these basins tend to be complex, with older fill often overlying melange generated by accretion. Prospective rocks are generally Neogene in age.

Southeastern Alaska is a region of Cenozoic transform plate motion where the northward-moving Pacific plate is being subducted beneath the eastern end of the Aleutian arc in the Gulf of Alaska. Where these two tectonic domains join lies a zone of highly complex structure, in the apex of the Gulf of Alaska. Plate convergence also dominates the region from Vancouver Island, southward along the Washington, Oregon, and northern California coast to the Mendocino triple junction. Along this segment of the Pacific margin, basins are mainly filled with Neogene beds that overlie structurally complex accreted sedimentary and volcanic rocks.

Central and northern California shelf basins formed in response to dextral Neogene transform movement between the North American and Pacific plates. Exploratory drilling in the 1960's indicates that some of the basins contain oil-bearing siliceous shales that may be similar to the Monterey Formation, which is now producing oil in the giant Arguello field.

The California Continental Borderland has several large bathymetric basins that contain prospective Neogene sediment sequences that wedge-out against basement ridges. Recent exploratory drilling in Upper Cretaceous and Paleocene strata on Santa Rosa–Cortes Ridge has produced disappointing results, because of poor reservoir rocks and immature source rocks.

Geologic trends of southern California extend into Mexico: shelf basins of northern Baja California are mainly filled with Neogene strata that overlie Franciscan-like accretionary rocks in the west and Cretaceous batholithic and older prebatholithic basement in the east. Central and southern Baja California is dominated by a Late Cretaceous and Paleogene forearc basin filled with siliciclastic sediment resembling Great Valley rocks. Exploratory drilling onshore and offshore indicates that potential source rocks are immature throughout the area; the source-rock immaturity reflects insufficient burial owing to long-term vertical tectonic stability of the granitic core of the Baja peninsula.

Despite immense volumes of sedimentary rock in waters less than 200 m deep, fewer than 120 rank wildcat wells have been drilled in Federal waters of the Western United States (Cook Inlet, Santa Maria, and Santa Barbara Channel excluded). In contrast, more than 550 wells have been drilled in the State of Oregon alone. Realistic assessments of petroleum potential can only be made when drilling provides data on source-rock volume, quality, and maturity, and the depth and age of porous and permeable reservoir rocks.

SEDIMENTOLOGY AND TECTONIC SETTING OF INTERMONTANE TERTIARY COAL-BEARING ROCKS, SOUTHWESTERN MONTANA

J. M'Gonigle, M. Kirschbaum, and J. Weaver

The intermontane Medicine Lodge and Horse Prairie basins of southwestern Montana are located between the Bitterroot Range on the west and south and the Tendoy-Pioneer Mountains on the east and north. The Medicine Lodge (ML) basin is adjacent to the Tendoy Mountains and lies east of the Horse Prairie (HP) basin; ML basin joins with the northern part of HP basin, but is separated from the southern HP basin by a north-trending spur of the Bitterroot Range, composed mainly of granite gneiss locally overlain by Paleozoic sedimentary rocks. These basins, covering an area of about 825 km^2, contain as much as 3,000 m of Eocene(?) to Miocene volcanic and sedimentary rocks. We mapped Tertiary rocks in the ML and southern HP basins as part of a study of coal depositional environments.

The oldest Tertiary sedimentary rocks in the region, preserved mainly in the Tendoy Mountains, are those of the syntectonic Paleocene Beaverhead Conglomerate, deposited during the Sevier-Laramide orogeny. Following erosion, extensive Eocene(?) volcanism in the region deposited as much as 760 m of andesitic lavas, tuff, and rhyolite in the ML and HP basins. After a second period of erosion, Oligocene(?) fluvial and lacustrine sediments filled the basins. An areally restricted but thick (360 m) freshwater limestone deposit in the southwestern part of the ML basin represents an open lacustrine facies that interfingers to the north with a marginal-lacustrine facies composed of shale, some conglomeratic sandstone, and carbonaceous shale and coal. Subsequent uplift caused the erosion of some of these sediments in the basins and the deposition of an alluvial fan sequence (as much as 427 m thick in the ML basin) in slight angular unconformity on the older sediments. Highlands to the south or west, where Tertiary volcanic rocks had been deposited directly on Proterozoic Belt sedimentary rocks, served as source areas for the clasts in the fans. The fanglomerates represent mid- and distal-fan facies, and grade laterally into a fluvial sequence (braided to meandering streams) of coarse conglomeratic to medium-grained sandstone and associated coal-bearing shaly swamp deposits. The bulk of the coal in the two-basin area is contained in the ML basin in these swamp and fluvial deposits, in beds averaging about 0.3–1.0 m thick. The swamp and fluvial deposits grade upward into a 1,250-m-thick open lacustrine facies of thin-bedded shale, tuffaceous shale, and minor limestone containing fish, ostracode, and plant fossils of Oligocene-Miocene age. These lacustrine deposits, which represent the reestablishment of a lake in the ML basin, can be mapped around the northern end of the spur into the HP basin, where they pass laterally into alluvial fill of mudstone, shale, and sandstone.

The basal Eocene(?) volcanic sequence and the overlying sedimentary sequence in the ML basin are identical to sequences in the HP basin, on the other side of the now mountainous north-trending gneissic spur separating the two basins. As no clasts of the gneiss that makes up the spur are found in the fanglomerates, and as the Tertiary beds now flanking the spur are everywhere tilted and (or) disrupted by faulting, it seems clear that the spur was exposed and eroded in post-Miocene time. Remnants of the volcanic sequence and overlying sedimentary rocks on differentially displaced structural blocks of Precambrian gneiss along the western side of the Tendoy Mountains indicate relative uplift of the Tendoys or ML basin subsidence by at least 3,000 m after Miocene time. These facts suggest that a single Tertiary basin was ancestral to the ML and HP basins, and that it probably once extended across part or all of the present northern Tendoy Mountains. The ancestral basin very likely also encompassed the areas of other nearby intermontane Tertiary basins, such as the Cabin Creek valley to the south, the Muddy Creek basin to the southeast, and perhaps the Big Hole basin to the north.

ANALYSIS OF SEISMIC REFLECTION LINES OVER PACIFIC CONVERGENT MARGINS

J. J. Miller and R. E. von Huene

Seismic reflection data recorded over convergent margins are difficult to interpret because of the many diffractions that mask primary structure and because the true geometrical relationships of steeply dipping faults and folded strata are distorted in standard, stacked record sections. We reprocessed data acquired over the eastern Aleutian Trench and the Middle America Trench off Guatemala and Peru using wave-equation migration techniques that were not available when the data were initially processed.

Wave-equation migration, applied after stacking, improved the quality of the structural information by eliminating diffractions. As we attempted to improve data quality further, we developed a processing scheme consisting of migration-velocity analysis performed on stacked record sections, migration applied before stacking, and restacking using stacking velocities determined after migration. We generated depth sections by applying refraction velocities observed in various geologic units to the equivalent units interpreted on the time sections.

The quality of all the resulting stacked record sections improved significantly because migration had eliminated diffractions and repositioned faults and folds into their true geometrical configuration. Specific improvements in resolution include (1) reliable stacking velocities of primary reflections previously masked by diffractions, (2) recognition of landward- and seaward-dipping fault-plane reflections in the Aleutian Trench, (3) recognition of gas hydrate reflections off Peru, (4) sharp definition of the boundary between accreted trench and sea-floor sediment and the truncated edge of the Peruvian continental crust, and (5) precise definition of decollements separating the subducted from the offscraped sediment sections in all the lines.

The processing procedure we developed requires additional man-hours and much computer time. However, the improvement in quality of the resulting seismic image is sufficient to justify the use of this procedure in areas of complex geology.

THERMAL-ENERGY STORAGE IN A CONFINED SANDSTONE AQUIFER AT ST. PAUL, MINNESOTA

R. T. Miller

The U.S. Geological Survey has been studying the hydrologic effects of storage and recovery of heated water in a deep sandstone aquifer in St.

Paul, Minnesota, since 1980. The USGS has designed a data-collection network, determined the hydrogeologic properties of the aquifer, conducted tests of hot-water storage cycles, and constructed computer models to simulate ground-water flow and thermal-energy transport.

The Aquifer Thermal Energy Storage (ATES) system, the data-collection network, uses a doublet-well design, with both wells completed in the Franconia-Ironton-Galesville aquifer. Water is pumped from one of the wells through a heat exchanger, heat is either added or removed, and the water is injected back into the aquifer through the other well. The injection/withdrawal wells are spaced 250 m apart.

Analysis of constant-rate, aquifer-test data indicates that the aquifer has four hydraulic zones that are areally anisotropic and whose average hydraulic conductivity ranges from 0.03 to 1.2 meters squared per day. Borehole-geophysical data indicate that the aquifer is horizontal and of uniform thickness between the injection/withdrawal wells. Laboratory analyses of core samples indicate that aquifer porosity ranges from 14 to 35 percent.

The experimental plan for testing the ATES system consisted of a series of hot-water injection, storage, and withdrawal cycles. Short-term tests consisted of four cycles approximately 24 days long, with each injection, storage, and withdrawal step of the cycle lasting approximately 8 days. A long-term-test cycle of 180 days consisted of 60 days each of injection, storage, and withdrawal.

Several computer models have been used to study the sensitivity of hydraulic and thermal model-input properties, to make preliminary evaluations of efficiency of the aquifer system, and to simulate the four short-term and one long-term experimental test cycles. Sensitivity analyses indicate that, in short-term heat injection, rock-heat capacity is the least sensitive property and thermal dispersivity the most sensitive. Preliminary model simulations indicate that injection/withdrawal rates and duration of heat storage can significantly affect the overall efficiency of the aquifer-thermal system. The period of simulation for modeling the short-term cycles was equal to the entire time period over which the four cycles were conducted, including periods between individual cycles. Model-computed aquifer-thermal efficiencies, defined as the total energy recovered divided by the total energy injected for equal pumping durations and rates, and final temperatures at the hot-water storage well were within plus or minus 2 percent and plus or minus 5°C, respectively, compared to those recorded in the field. Model simulation of long-term test cycles required an increase in the areal descritization to account for a larger area of stored heat. Field-recorded aquifer-thermal efficiency and final well-head temperatures were 68 percent and 67°C, respectively, while model simulation gave aquifer-thermal efficiencies and final well-head temperatures of 67 percent and 68°C, respectively.

ENHANCED ANALYSIS OF TRACE-ELEMENT CHARACTERISTICS OF BITUMINOUS COALS USING THE PROTON (PIXE) MICROPROBE

Jean A. Minkin, E. C. T. Chao, and Herma Blank[5]

Microprobe methods have proven to be valuable techniques in coal-quality studies, for example in in-place direct determination of organic sulfur content in coal macerals, and modes of occurrence of such elements as As, Se, Na, and Cd. In routine electron probe microanalysis (EPMA), the practical lower limit of detection for most elements is about 100 ppm. Therefore, the development of microprobes based on proton-induced X-ray emission (PIXE) has provided an important extended capability for quantitative determination of elemental concentrations in individual maceral and mineral grains: the detection limit for the analysis of most elements using the proton microprobe is 1–10 ppm.

We were encouraged by the results of our first PIXE study (1982), on vitrinites in a series of vitrites, selected from along the length of a single drill-core sample (M1) of the J and I coal beds of the Ferron Sandstone member of the Mancos Shale, Emery County, Utah. We therefore selected two companion drill cores, M3 and M5, for similar analysis, to examine trace-element variations laterally as well as vertically. Locality M3 is separated from M1 by approximately 3,700 ft (1,125 m), and M5 is an additional 4,350 ft (1,300 m) in the same direction from M3. In addition, vitrites from selected depth intervals of a columnar section of Upper Freeport coal from Indiana County, Pa., and a columnar section of No. 6 coal, Webster County, Ky., were analyzed to develop preliminary profiles of trace-element variation

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with depth and compare the data for these eastern coals with those of the Utah coal. Analyses were all carried out on vitrinite group macerals because the vitrinite content in all these coals is generally about 80 volume percent or more. Hence, vitrinites are probably the major source of trace elements attributable to macerals in these coals.

Trace-element characteristics of the three Utah drill-core samples are generally similar to one another. Most notable is the consistent general trend of increase in iron concentration (unrelated to iron sulfide) from top to bottom of the I coal bed (<20 to about 1,400 ppm). There is a parallelism of variation in elements such as Ti, Zr, and Cr in vitrinite for the three cores, which in turn resembles the trends for Si and Al determined by EPMA, suggesting that these elements are largely associated with submicroscopic clay particles. In the Upper Freeport coal bed, V, Cr, Ni, Zn, Ga, and Ge are all present at higher concentrations in vitrinites from near the bottom of the bed than near the top, at the one location studied. No obvious systematic trends or variations were noted for the Kentucky No. 6 sample. Bromine is present in the two eastern coals at higher concentrations (Upper Freeport about 100 ppm and Kentucky No. 6 about 20 ppm) than in the Utah coal (<1 ppm), while Sr is generally higher (30–300 ppm) in the Utah samples than in the eastern samples (10–30 ppm).

These examples of data obtained illustrate the sensitivity of detection obtainable with the proton microprobe in analysis of coal macerals. Such data will be important in tracing the geochemical conditions of deposition and diagenesis of a coal bed, and in assessing potential applications and problems of combustion, gasification, or liquefaction of particular coals.

REGIONAL CORRELATION SECTIONS ACROSS THE NORTH SLOPE OF ALASKA

C. M. Molenaar, K. J. Bird, and T. S. Collett

Since the discovery of the giant Prudhoe Bay field in 1968 and the subsequent exploration in northern Alaska, new data have added immensely to the understanding of the stratigraphy of rocks underlying the North Slope coastal plain. The stratigraphic section consists of two sequences, the northern-derived Ellesmerian sequence and the overlying southern- and southwestern-derived Brookian sequence. The Ellesmerian sequence consists of (1) Mississippian through Triassic semistable platform carbonate and clastic rocks, zero to 2,500 m thick; (2) southward-prograding shelf to basinal Jurassic to earliest Cretaceous shales, zero to 1,100 m thick; and (3) less than 100 m of northward-transgressing Hauterivian-Barremian (Early Cretaceous) shale with a lenticular basal sandstone that unconformably overlies progressively older rocks to the north.

The Brookian sequence displays much greater time-transgressive facies relationships across the North Slope than does the Ellesmerian sequence. It is an easterly to northeasterly prograding wedge of Aptian(?) (Lower Cretaceous) through Tertiary clastic rocks as much as 4,000 m thick. In ascending order, this sequence consists of (1) less than 300 m of Aptian(?) to Maestrichtian basinal shale and bentonite, the lower part of which is generally organic rich; (2) as much as 3,000 m of Albian to Eocene basin-slope or prodelta shale with turbidites in the lower part; and (3) as much as 2,400 m of Albian to Quaternary shallow marine and nonmarine deltaic and alluvial-plain sandstone, shale, and conglomerate. A network of regional well-correlation sections across the North Slope, based in part on micropaleontologic and seismic data, shows that these different facies of the Brookian sequence are coeval with each other across depositional strike, and that most of the nomenclature established in the western North Slope is not applicable to the eastern North Slope.

COMPUTERIZED ASSESSMENT OF THE COAL RESOURCES AND GEOLOGY OF THE SAN JUAN BASIN, NEW MEXICO

Carol L. Molnia, Antoinette L. Medlin, Kathleen K. Krohn, Joseph T. O'Connor, Laura H. Biewick, Nancy K. Gardner, and Lewis W. Boger

The National Coal Resources Data System (NCRDS) of the U.S. Geological Survey recently produced resource estimates, and accompanying computer-generated illustrations, for a study of coal in the San Juan Basin, New Mexico. This study is part of a larger study of the coal resources and coal quality in the State of New

Mexico, done in cooperation with the New Mexico Bureau of Mines and Mineral Resources.

A working data base of stratigraphic information on the Cretaceous Fruitland and Menefee Formations, the two major coal-bearing units within the San Juan Basin, was retrieved from the NCRDS master data base for New Mexico by use of the PACER data storage and retrieval system on a 32-bit minicomputer. These data were reviewed for consistency and correctness, additional data were coded and added, and retrievals were then made for drill holes that penetrated the entire thickness of the Fruitland or Menefee Formations, within the digitized boundary areas.

The coal resources for both formations were calculated from this data set in GARNET, one of the graphic analysis and volume calculation software systems of NCRDS. In addition, the same Fruitland Formation coal data set was analyzed by the geostatistical method, kriging. Because of the lenticular nature of the coal beds and the large area under study, the resource assessments were not made for individual coal beds but rather for total coal in a formation.

The GARNET software uses a point file location, a grid file of coal thickness, and a boundary file to calculate the volume of coal; then, the density factor for the rank of coal is applied to produce a coal tonnage estimate. By this method, the Fruitland Formation is estimated to contain 168 billion short tons of coal and the Menefee Formation is estimated to contain 21 billion short tons of coal, within the New Mexico part of the San Juan Basin. The estimate was presented in three ways: as a single resource tonnage; as measured, indicated, inferred, and hypothetical category tonnages; and as tonnages in various land ownership and overburden categories.

The kriging method considers the spatial variability of data and produces estimates which are unbiased and have minimum error variance. Total in-place coal resources estimated by this method for the Fruitland Formation are 160 billion short tons, which is within 5 percent of the GARNET estimate. The kriging method was also used to help design future data collection programs by optimizing the location of sample points; hypothetical drill-hole locations were added to the kriged data set for assessment of their impact on the precision of the estimate.

In addition to the actual resource calculations, the study produced several computer-generated illustrations of the geology of the San Juan Basin. A color graphics package that models stratigraphic surfaces in three dimensions was used to display, through interlocking panels in various orientations, the interval containing the Kirtland Formation, Fruitland Formation, Pictured Cliffs Sandstone, and the Lewis Shale and its Huerfanito Bentonite Bed. Illustrations of the structure of the basin on the base of the Dakota Sandstone were also developed, as was a correlation diagram for the Fruitland coal zone. The GARNET software was used to illustrate generalized land ownership patterns as well as to contour coal isopachs and overburden.

AN EXPLORATION MODEL BASED ON A GENETIC MODEL FOR THE TABULAR-TYPE VANADIUM-URANIUM DEPOSITS IN THE HENRY BASIN, UTAH

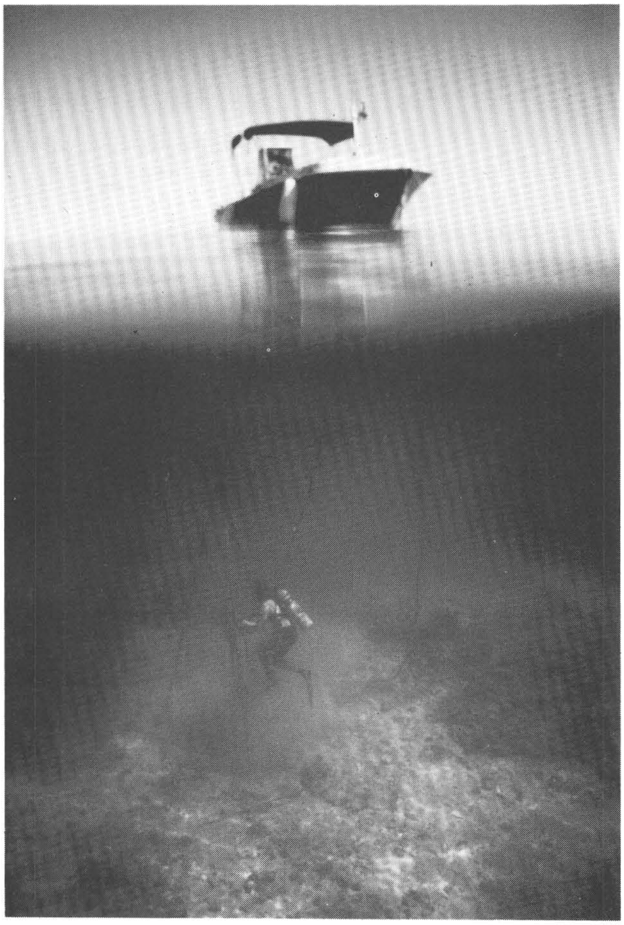
H. Roy Northrop, Fred Peterson, Gene Whitney, and Martin B. Goldhaber

The sandstone-dominated Salt Wash Member of the Upper Jurassic Morrison Formation hosts tabular-type vanadium-uranium deposits in the Henry basin, Utah. The deposits are, in general, typical of vanadium-uranium deposits in the Colorado Plateaus province. Previous work allowed us to construct a genetic model of these deposits and to identify a number of key aspects of the ore-forming process that can now be combined to make a simple yet precise exploration model.

The key features of ore genesis are as follows:

1. Vanadium-uranium mineralization occurred at and immediately below a nearly basin-wide density-stabilized brine-meteoric water interface that migrated up stratigraphic section with time.
2. Economic vanadium-uranium deposits formed in intrabasinal synclines.
3. Detrital organic matter, which was preferentially preserved by specific sedimentological controls, was a necessary component of the mineralizing process.
4. Uranium was leached from the host rocks up paleohydrologic gradient and up stratigraphic section from the deposits, and enriched down the paleohydrologic gradient from the largest deposits.

The mineralogic fingerprint left by the brine–meteoric water interface, organic-enriched sandstones, intrabasinal synclines, and rocks leached of uranium are geologically identifiable features



Core drilling on a patch reef in Enewetak lagoon. Diver operates drilling equipment that is powered by hydraulic pumps in RV HALEMIDA, 10 m overhead. Diver: J. Harold Hudson. Photograph by R. B. Halley.

that define deposit locations. Dolomite and a vanadium-bearing clay mineral formed in direct response to the brine–meteoric water interface throughout the basin, thus marking the penecon-cordant stratigraphic intervals where the mineralizing reactions occurred irrespective of uranium ore grade. Detrital organic matter was preserved close to black, organic-rich mudstones deposited in small anoxic lakes. These lakes occurred at the low-energy end of the Salt Wash fluvial system. The brine–meteoric water interface was sharply defined within intrabasinal synclines, whereas mixing of the brine and meteoric water over intrabasinal anticlines resulted in a poorly defined solution interface. These diffuse solution interfaces reduced the effectiveness of the vanadium-uranium concentrating reactions, and prevented ore-grade mineralization on the anticlines. Large-scale uranium distribution patterns throughout the basin are useful because rocks leached of uranium are a necessary part of the ore-forming process. Th:U ratios are a very sensitive indicator of this uranium removal.

Elements of our exploration model involve taking the geologically identifiable features associated with each key aspect of the ore genesis model to identify successively smaller targets. Initially, identification of potential source rocks leached of uranium on the up-paleohydrologic side of a basin not only identifies a required process but also defines a large-scale target. The location of suitable intrabasinal synclines through detailed sedimentologic and stratigraphic studies then defines possible sites for vanadium-uranium concentration. This effort yields somewhat smaller scale targets. The distribution of those mudstones with associated organic-matter-enriched sandstones is predictable by sedimentological analysis, yielding even smaller targets. At that point, detailed mineralogy defines each interval that hosted a brine–meteoric water interface. The limits of orebodies are defined where this interval projects across the organic-enriched sandstones.

CONTROLS ON DISTRIBUTION OF ORE IN SO-CALLED "UNCONFORMITY-TYPE" URANIUM DEPOSITS IN AUSTRALIA AND IMPLICATIONS FOR UNITED STATES URANIUM RESOURCES

C. J. Nutt, David Frishman, R. I. Grauch, J. T. Nash, and K. R. Ludwig

The Jabiluka and Ranger "unconformity-type" uranium deposits in the Pine Creek geosyncline, Australia, are hosted by metasedimentary rocks of the Early Proterozoic Cahill Formation and are beneath the regional unconformity separating these metamorphic rocks from the overlying sandstones of the Middle Proterozoic Kombolgie Formation. U-Pb radiometric ages show that at Ranger, primary ore formed more than 1,720 m.y. ago, well before deposition of the Kombolgie Formation (1,648 Ma) and contemporaneous with a period of postorogenic granitic intrusions. The Jabiluka deposit formed about 280 million years later, during a period in which no major thermal event has been recognized.

In both deposits, uranium ore occurs in breccias and veins and as disseminations in intensely chloritized pelitic, in places graphitic, schists.

Brecciation has previously been attributed to collapse following solution of carbonate, but at Jabiluka siliceous breccias that occur in or adjacent to graphite schist and along the contact separating carbonate and graphite schist retain textures indicative of tectonic origin. We propose that brecciation is largely the result of brittle deformation and is particularly concentrated in siliceous interlayers in the graphite schist and along the contact separating carbonate and schist. Faulting and silicification coupled with carbonate collapse also brecciated the rocks at Ranger.

Alteration at the two deposits is similar and occurs in both the metasedimentary rocks and, to a lesser extent, in the overlying sandstone. Magnesium-rich chlorite is the most prominent alteration mineral in these deposits, but apatite, tourmaline, white mica, and quartz were also introduced. At Ranger the alteration is more intense and primarily restricted to the orebodies, whereas at Jabiluka the alteration is more pervasive and extends far into the surrounding rocks. Cross-cutting relations among chemically distinguishable chlorites testify to the influx of numerous pulses of fluid with different and probably evolving compositions. Although alteration is most intense in the ore zones, much of the observed alteration occurred after uraninite deposition and only locally redistributed preexisting ore.

Ranger's pre-1,720 Ma age indicates that the unconformity and overlying sandstone played no role in primary concentration of the ore, although the Kombolgie no doubt helped preserve the deposit from later erosion. At the younger Jabiluka deposit, the role of the unconformity and the rocks above it is less clear, however, and whether or not the lithology of the cover rocks is important is as yet unresolved. Jabiluka possibly contains remobilized uranium, perhaps from a preexisting Ranger-type deposit, that was preferentially concentrated in the brecciated areas.

Because they are both large and high grade, "unconformity-type" deposits have been very attractive exploration targets for the last 15 years. Numerous areas in the United States have been investigated for this type of deposit, including the terrane beneath the Jacobsville Sandstone in Michigan and the area beneath the Sioux Quartzite in Minnesota and South Dakota. In both these areas, the major similarity to productive "unconformity-type" districts is simply the existence of a fluvial Proterozoic sandstone. However, knowing that the sandstone was, in at least one case, irrelevant to primary ore deposition makes areas like those mentioned much less favorable for deposits similar to Ranger. Conversely, the apparent structural control on localization of ore at Jabiluka and Ranger implies that structure in the metasedimentary sequence may be a more relevant constraint on exploration strategies and resource assessment than the mere existence of an unconformity.

DISCRIMINANT ANALYSIS OF TRACE ELEMENTS IN COAL BEDS OF EARLY AND MIDDLE PENNSYLVANIAN AGE FROM THE CENTRAL APPALACHIAN BASIN

J. T. O'Connor

Sixty-two of the sixty-three trace elements analyzed for coal samples as part of the U.S. Geological Survey Coal Geochemistry program were examined using the Fisher discriminant analysis technique, to determine if distinguishing geochemical characteristics exist for the coal beds of the Lower and Middle Pennsylvanian section of the Central Appalachian basin. Analyses were selected representing all samples (channel, bench, composite, grab, and core) with relatively low (<20 percent) ash content and were converted to an ash basis prior to examination. In order to assure that all samples were analyzed with comparable techniques, accuracy, and precision, only the more recent (later than July 1, 1975) samples from the USCHEM file of the National Coal Resources Data System data base were utilized. Elements with fewer than 50 percent unqualified analyses were dropped from consideration; elements with fewer than 75 percent unqualified analyses were examined carefully before inclusion or exclusion from the study. Other qualified analyses were converted from trace, less-than, greater-than, blank, not-reported, or interference qualifications according to U.S. Geological Survey protocol. Stratigraphic sample-population distribution ultimately restricted this study to analysis of samples from the Pocahontas No. 3, Pocahontas No. 4, Pocahontas No. 6, Eagle, and Sewell coal beds.

Using the discriminant analysis technique, the author was able to distinguish unique geochemical differences between all of the coal sample groups studied. Twenty-four Eagle coal samples were distinguished from 26 Sewell coal samples with no exceptions and a very high significance test; the primary discriminating elements selected by the technique were Ce, Se, Ta, Zr, Sr, and B. Fifty-two Pocahontas No. 3 and No. 4 coal samples were distinguished from 24 Eagle coal samples with no exceptions and a very high significance test; the primary elements selected by the technique were B, Ga, Pb, Co, Ce, and Sc. Fifty-two Pocahontas No. 3 and No. 4 coal samples were distinguished from 26 Sewell coal samples with one exception and a high significance test; the primary elements selected by the technique were Y, B, Se, Sc, Zn, and Th. Thirty-seven Pocahontas No. 3 coal samples, 15 Pocahontas No. 4 coal samples and 7 Pocahontas No. 6 coal samples were distinguished from each other with no exceptions and a moderately high significance test. The primary elements selected by the technique were Se, V, Ni, Ag, Co, and La.

The discriminant analysis technique provides the coal geochemist a useful tool for determining unique geochemical characteristics of coal beds out of extensive collections of trace-element data. Such geochemical characteristics should aid the coal geochemist studying differences in depositional environments existing at the time of coal bed formation and should help to correlate "orphan" coal beds with those for which geochemical data exist.

INDUCED SEISMICITY AND THE STATE OF STRESS AT THE GEYSERS GEOTHERMAL AREA, CALIFORNIA

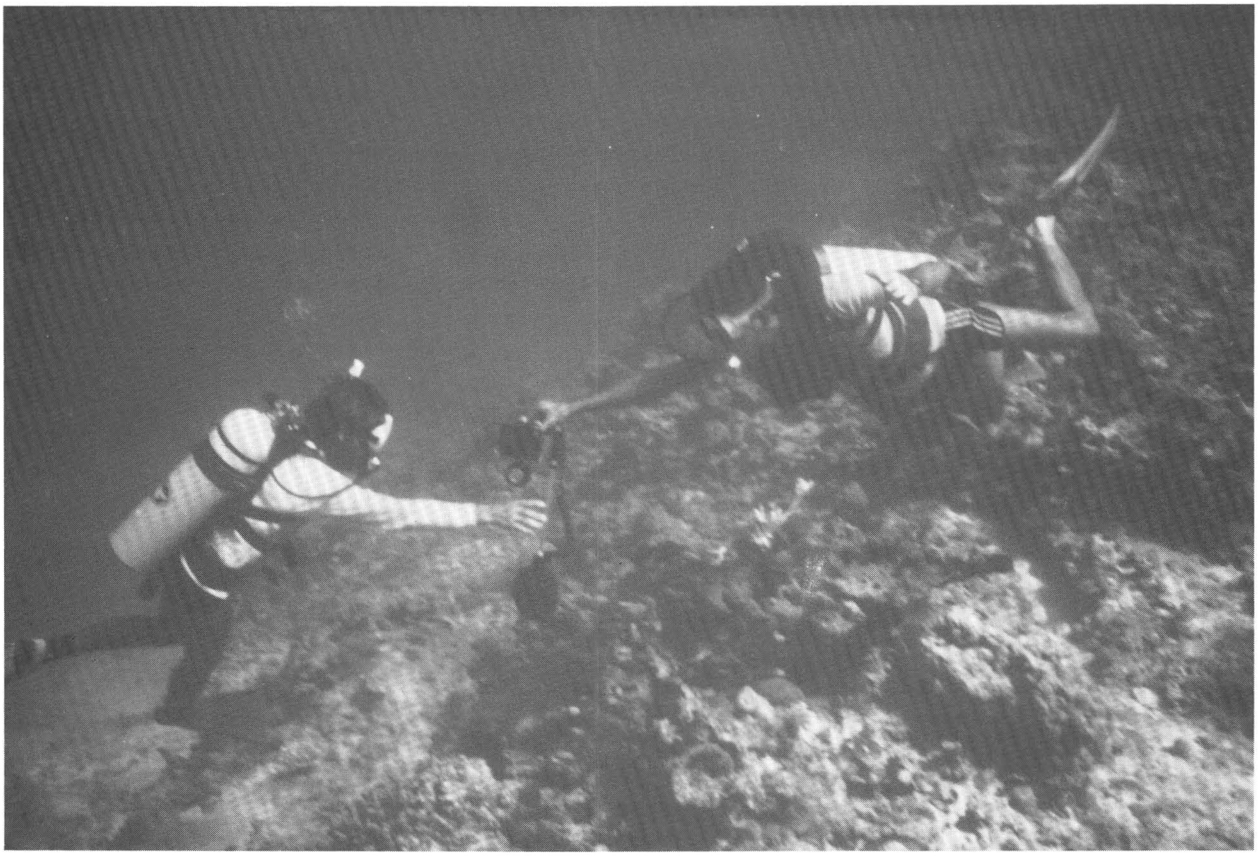
D. H. Oppenheimer

Previous studies of temporal and spatial distributions of seismicity at The Geysers, California, geothermal field demonstrated that activities related to steam withdrawal induced earthquakes. To gain insight into the inducing mechanism, the stress field at The Geysers was investigated through an analysis of 210 earthquake fault-plane solutions determined from *P* wave first motions. The earthquakes were recorded by the U.S. Geological Survey's Central California Seismic Network for the period April 1984 through May 1985. The suite of earthquakes spanned the depth range of 0.1 to 5.4 km and were located from at least 15 observations out to epicentral distances of 60 km.

Induced earthquake activity at The Geysers occurs on fault planes whose orientations vary greatly over epicentral distances as small as 1.0 km. Estimates of the orientation and relative magnitudes of the principal components of the stress field show that the vertical component of the stress field exceeds that of the horizontal below a depth of 1 km. This results in depth-dependent fault-plane solutions whereby the earthquakes at depths less than 1 km mostly exhibit strike-slip to reverse mechanisms, whereas deeper earthquakes show increasing tendency for normal mechanisms. Below 2 km depth The Geysers appears to be undergoing uniaxial extension with the axis of extension oriented at approximately 106° azimuth.

The good agreement between the local stress field below 1 km calculated from seismic data and that inferred from regional geodetic networks indicates that the regional tectonic stress is much larger than the stresses induced locally through geothermal production activities. The presence of large depositional basins to the north-northwest of The Geysers, together with normal focal mechanisms determined at The Geysers and the Konocti Bay fault zone, suggests that extension occurs over the entire region between the Maacama and Bartlett Springs fault zones. It is difficult to attribute this extension at The Geysers to tectonics associated with typical pull-apart basins because no basins are evident in the regional topography and extent of the master strike-slip faults is not known. However, regional extension is compatible with the wide-spread presence of Quaternary volcanism in the Clear Lake area.

These results still do not establish the earthquake-inducing mechanism. However, the data permit a rather detailed description of the style of faulting and location of earthquake activity with respect to geothermal well positions. They indicate that the activity above a depth of 3.5 km occurs within several hundred meters of the wells and likely occurs in the immediate vicinity of fractures supplying steam to the wells. The most likely mechanism involves stresses induced by reservoir contraction, due either to pore collapse of the reservoir rock as water migrates out into the permeable fractures, or to thermal contraction resulting from production-related pressure declines in the reservoir. The large amount of seismicity below 3.5 km depth reflects either steam communication between the wells and deeper regions of the geothermal reservoir through an extensive fracture network, or stress perturbations induced via reservoir contraction at shallower depths.



Divers pass camera during photo-documentation of patch reef in Enewetak lagoon. Studies of modern depositional environments provide a basis for comparison with similar ancient deposits that are reservoirs for hydrocarbons. Divers: J. Harold Hudson (left); Eugene A. Shinn (right). Photograph by R. B. Halley.

STRUCTURE AND PETROLEUM POTENTIAL OF PALISADES ROADLESS AREA, IDAHO-WYOMING THRUST-BELT SALIENT NEAR JACKSON, WYOMING

Steven S. Oriel and David W. Moore

The U.S. Forest Service Palisades Roadless Area encompasses 386 square miles of the Snake River Range and lies along the northern end of the Idaho-Wyoming salient of the Cretaceous and early Paleogene Cordilleran foreland thrust belt southeast of the eastern Snake River Plain. The Teton Range fault block abuts the area on the north; Jackson, Wyoming, lies 7 miles east of the area's northern boundary. Bounding the area on the southwest are Swan and Grand Valleys, within the Neogene Swan Valley graben. The Snake River Range lies between the Salt River Range, on the south, and the Big Hole Mountains on the north.

Geologic mapping, begun in 1980 and recently completed, confirms the presence of successively structurally higher (from northeast to southwest) and older thrust sheets including the Jackson, Darby, Absaroka, and St. John allochthons. Several discontinuously exposed thrust slices (with various local names) are exposed on the southwest. The complexly folded and imbricately faulted thrust sheets consist of southwestward-thickening, mainly continental shelf strata, from the Cambrian Gros Ventre Formation to the coal-bearing Cretaceous Frontier Formation; these lithostratigraphic units are identical to those in the petroliferous southern part of the Idaho-Wyoming thrust-belt salient. Anticlines and fault wedges exposed within the Snake River Range resemble proven subsurface structural traps defined in the southern Fossil basin (southwesternmost Wyoming) by both seismic reflection surveys and drilling. Moreover, favorable additional structures plunge beneath exposed thrust faults.

Our studies do not support the presence of the north- to northeast-dipping Cache Creek thrust fault, inferred by others to underlie Teton Pass. If the fault were there, Mesozoic and upper Paleozoic strata beneath it would constitute potential hydrocarbon exploration targets. However, Neogene strata mapped by us are cut by northwest-trending extensional faults at Teton Pass, and synorogenic detrital evidence for movement on the Cache Creek fault is absent. We conclude that the Teton Range fault block, containing very thin cratonic Paleozoic and Mesozoic cover rocks, was broken and rotated toward the Snake River Plain volcanic rift long after the far thicker thrust belt strata were juxtaposed upon it by thrusting; the range formed as the crust was extended to form the Snake River Plain from Miocene time on.

Hydrocarbon source beds, potential reservoir strata, fluid seals, structures, and hydrocarbon thermal maturities within thrust sheets of the Palisades area are comparable to those in large producing oil and gas fields in southwesternmost Wyoming and northern Utah. Moreover, eastward thinning and facies changes of both continental shelf strata and the overlying Mesozoic synorogenic units make stratigraphic traps probable in many strata which dip predominantly to the west. The petroleum potential for the Palisades area is thus high, in thrust sheets of the Snake River Range south of Teton Pass.

MOVEMENT AND FIXATION OF URANIUM ON ORGANIC MATTER IN A LATE QUATERNARY URANIUM DEPOSIT, STEVENS COUNTY, WASHINGTON

James K. Otton and Robert A. Zielinski

Studies of a recently discovered, ore-grade accumulation of uranium in upper Quaternary, organic-rich sediments have provided a rare opportunity to study the movement and fixation of uranium in a natural setting. The deposit is hosted by valley-fill sediments that underlie the north fork of Flodelle Creek, in Stevens County, Washington. These sediments are as much as 5 m thick and rest on glacio-fluvial sediments 12,000–13,000 years in age. The local country rock is a two-mica quartz monzonite which is mostly covered by glacial drift.

Waters moving through these organic-rich host sediments are derived from seasonal runoff in the 4.2-km^2 drainage basin or from springs on the slopes and the valley floor. Stream, spring, and shallow ground waters in the valley-bottom sediment contain 17–318 ppb uranium—compared to a regional background of 1–2 ppb. No other measured major or trace chemical species are as concentrated. Values for pH range from 5.85 to 7.55. The high concentrations of dissolved uranium, absence of H_2S odor, and the presence of dissolved nitrate are compatible with mildly oxidizing conditions. In filtered water samples, a high covariation of uranium with the major cations (Ca^{2+}, Na^+, and Mg^{2+}), major anion (HCO_3^-), total dissolved solids, and conductivity all suggest that uranium is carried in a dissolved form. Uranium does not correlate with dissolved organic carbon. Thermodynamic calculations indicate that uranyl carbonate and phosphate are the major inorganic aqueous complexes. Factor analysis of the water data and reanalysis of more finely filtered samples indicate that some uranium is carried by colloidal particles of clay, organic matter, and hydrous iron oxides. Calculations of mineral solution equilibria suggest that the measured waters are undersaturated with respect to uranous- and uranyl-bearing minerals if the ambient Eh exceeds 0.1 volt. Compared to coexisting waters, peat collected near the present surface of the deposit sediments is enriched in uranium several thousandfold, in quantitative agreement with predictions based on a sorption-ion exchange model in a 1964 study of A. Szalay.

Chemical analyses of sediments from 72 intervals in 4 cores as much as 2.9 m deep indicate uranium contents that vary from <100 to 4,470 ppm, and that correlate strongly (r=0.8622) with organic matter (0.5–60 percent dry weight, estimated by loss on ignition). R-mode factor analysis, chemical variation diagrams, and depth profiles of measured species indicate that uranium contents are largely controlled by the relative proportions of uranium-enriched organic matter and uranium-poor detrital mineral matter. Virtually all other chemical species are controlled principally by the relative abundances of the three major detrital components: light minerals such as feldspar and quartz, heavy minerals such as iron and titanium oxides, and volcanic ash. Total sulfur contents tend to covary with organic matter and uranium content in the shallow parts of all the cores. However, deeper in some cores sulfur and uranium values are higher than would be expected from the relatively low organic matter content, suggesting that sulfur species may be affecting uranium content locally.

Fission-track radiography of thin sections of organic matter in the sediment and uranium contents of various size fractions of peat indicate that uranium preferentially associates with fine-grained, structureless organic matter, suggesting that surface area and degree of humification of organic matter are important controls on uranium fixation.

The results to mid-1985 support a working hypothesis that peat in the shallower parts of the system initially adsorbed uranium. Ongoing studies of sulfur speciation, bacteria, and degradation of the organic matter focus on possible reduction mechanisms of uranium in lower parts of the deposit.

ACCRETION, SUBDUCTION, AND UNDERPLATING IN SOUTHERN ALASKA—INITIAL RESULTS FROM THE TRANS-ALASKA CRUSTAL TRANSECT

Robert A. Page, David L. Campbell, George Plafker, Gary S. Fuis, Warren J. Nokleberg, Elizabeth L. Ambos, Walter D. Mooney, and Michael A. Fisher

The Trans-Alaska Crustal Transect (TACT) is a major U.S. Geological Survey project aimed at determining the structure and evolution of the Alaskan crust along a north-south corridor paralleling the trans-Alaska pipeline and extending offshore across the Pacific and Arctic continental margins. Begun in the summer of 1984, TACT work to mid-1985 has incorporated geologic mapping, petrologic and geochronologic studies, seismic refraction/wide-angle reflection profiling, and gravity and magnetic investigations. Vertical reflection profiling and magnetotelluric sounding will begin in 1986. The transect was launched in the Chugach Mountains and Copper River Basin in southern Alaska; over the next 5 years it will proceed northward to Prudhoe Bay and across the continental margins.

In the first two seasons, TACT investigations focused on three abutting accreted terranes and the underlying shallow lithosphere. From south the north, the terranes are (1) the Prince William terrane (PWT), composed of an accreted Paleocene and Eocene deep-sea fan complex, oceanic volcanic rocks, and pelagic sediments; (2) the Chugach terrane (CGT), composed of accreted Upper Cretaceous flysch and oceanic basaltic rocks, accreted and subducted(?) Upper Jurassic to Lower Cretaceous sheared melange, and subducted(?) Lower(?) Jurassic or older blueschist/greenschist; and (3) the composite Wrangellia/Peninsular terrane (WRT/PET), consisting primarily of upper Paleozoic andesitic arc rocks with associated mafic and ultramafic plutonic rocks, an overlying Triassic sedimentary and volcanic sequence, and superposed intrusive and extrusive magmatic rocks of the Jurassic Talkeetna arc.

The PWT is thrust relatively northward beneath the CGT along the Contact fault system, and the CGT is thrust at least 40 km northward beneath the WRT/PET along the Border Ranges fault system. At the southern margin of both the CGT and WRT/PET, shallow high-velocity bodies (depths $\gtrsim$2–3 km and 1 km; V_p=6.8–7.1 km/s and 6.1–6.4 km/s, respectively) characterized by magnetic and gravity highs reflect uplift of mafic and ultramafic basement along these thrusts. The Border Ranges fault system apparently soles into a subhorizontal low-velocity layer of uncertain origin flooring the northern CGT and the southern WRT/PET at about 7–9 km depth. The Contact fault system may sole into a deeper, gently north dipping low-velocity layer at about 9–12 km. Three additional north-dipping low-velocity layers are defined between about 15 and 35 km depth beneath the CGT. We interpret the four dipping low-velocity layers and the subjacent high-velocity (V_p=7.8–8.3 km/s) layers as subducted assemblages of oceanic crust and mantle rocks. Based on the occurrence of earthquakes in the lower two assemblages, we infer that active subduction involves the lower two assemblages and that the upper two have been underplated onto the continental plate.

BOREHOLE GEOPHYSICAL APPLICATIONS IN THE CHARACTERIZATION OF GEOTHERMAL ENERGY RESOURCES

F. L. Paillet, R. H. Morin, and W. S. Keys

Borehole geophysical measurements represent an important technique for the evaluation of geothermal resources, but the hostile environment and complex geology of geothermal reservoirs make progress in geothermal logging quite slow. Geophysical logs are especially useful because they characterize rock properties at in-place conditions. Continuous well logs provide the resolution required to identify sets of fractures and low-permeability caprock layers that may be less than a few meters thick. This continuity and spatial resolution are required to incorporate discontinuous core intervals and surface geophysical data into a consistent reservoir model.

Ongoing research in geothermal well logging can be separated into three components: (1) development of equipment capable of withstanding the high temperatures, large pressures, and corrosive fluids encountered in geothermal reservoirs; (2) understanding the geophysical response of conventional and nonconventional logging devices to spatially complex patterns of geochemical alteration; and (3) improving methods for identifying and characterizing fractures in sedimentary, igneous, and metamorphic rocks. Significant progress in all aspects of geothermal-logging research is expected when a proposed deep borehole in the Salton Sea basin of southern California becomes available in late 1985. Maximum temperature in this 3,000-m-deep well is expected to be about 370°C; dissolved-solids concentrations of the brine are expected to be as much as 265,000 mg/L.

Current equipment development emphasizes adaptation of conventional petroleum-industry technology to higher temperatures and greater pressures, and testing of new materials and designs for cableheads and seals that will continue to function properly at extreme environmental conditions. A new logging cable with Teflon insulation and corrosion-resistant alloy armor is now being purchased by the U.S. Department of Energy for testing at the Salton Sea site by the U.S. Geological Survey.

Analysis of complex alteration patterns associated with geothermal regions requires sophisticated interpretation techniques and modifications in logging-tool configuration. Initial research focused on the application of standard computer-analysis techniques such as cross-plotting of nuclear logs and histograms of log values to identify zones of alteration. Gamma spectral logs have been used at the Raft River, Idaho, and Roosevelt Hot Sprints, Utah, geothermal areas to further characterize the alteration minerals adjacent to boreholes. We are currently refining techniques for analysis of gamma spectral logs, and applying computerized statistical methods to identifying alteration types and clay sequences.

Most fluid production in geothermal reservoirs is associated with natural fractures. Fracture conduits may be important in the circulation of ground water through geothermal systems. Our research has emphasized the development of both fracture-characterization equipment capable of withstanding the geothermal environment, and new analytical techniques for fracture characterization. We devote a major part of our existing tool development effort to the acoustic borehole televiewer, which produces an ultrasonic image of the borehole wall. New fracture-characterization methods are based on the quantitative interpretation of acoustic attenuation using recently designed, low-frequency, acoustic logging equipment. These techniques have been verified at several nongeothermal sites on the Canadian Shield, and will be further tested in the proposed Salton Sea deep borehole.

The requirement to relate the great detail inherent in geophysical logs with the large-scale information obtained from surface geophysical surveys is a critical part of geothermal exploration. An example of this approach is the correlation of borehole acoustic surveys with vertical seismic profiles (VSP). One preliminary study was performed on a gabbroic batholith in eastern Massachusetts (fig. 1), and several additional studies are planned.

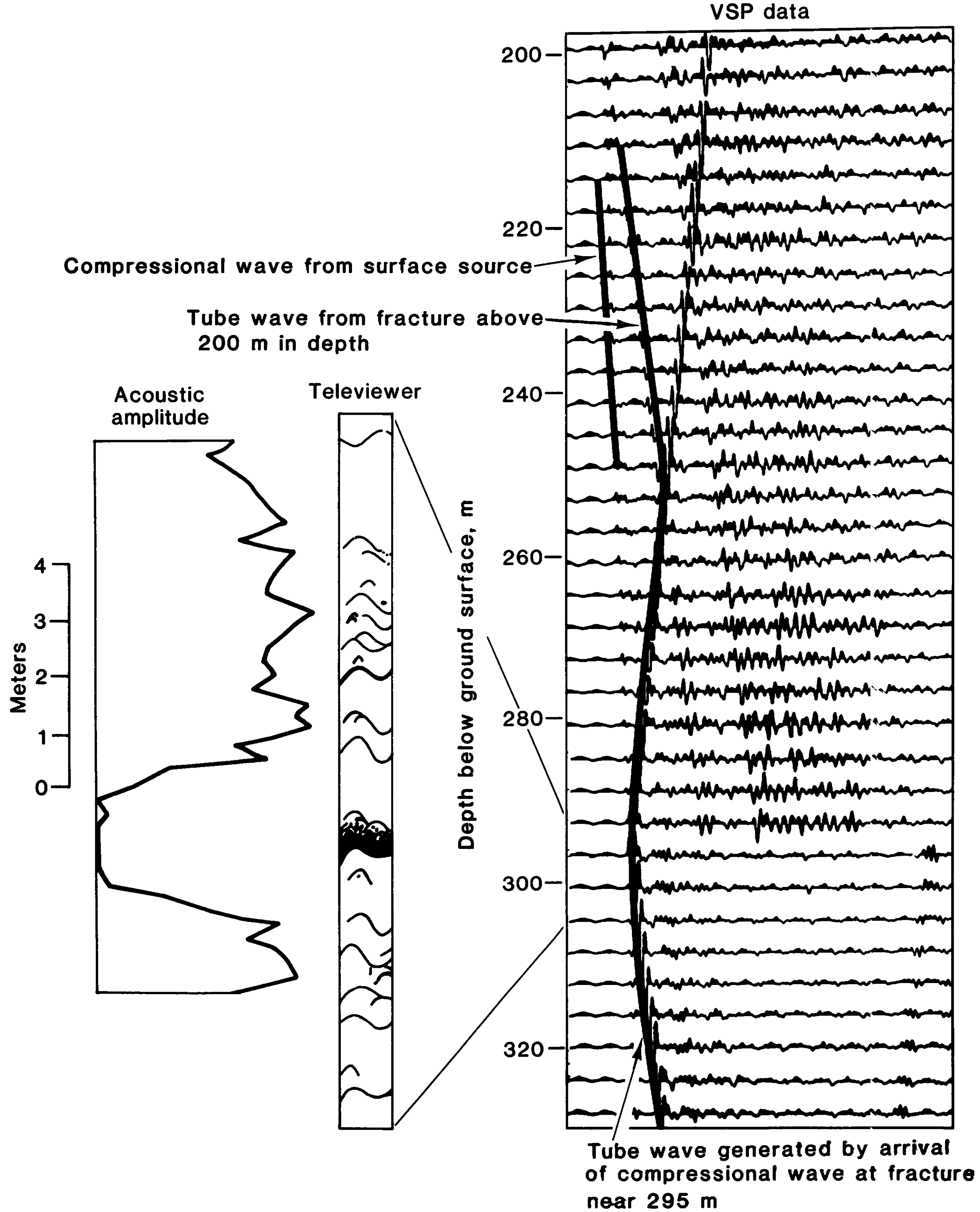


FIGURE 1.—Comparison of acoustic waveform log amplitude attenuation with VSP tube wave generation for a large fracture set at nearly 300 m in depth in northeastern Massachusetts.

THERMAL MATURITY MAPPING OF THE UNITED STATES

James G. Palacas

The measured response of sedimentary organic matter to the combined effects of intensity and duration of heating in the Earth is commonly referred to as thermal maturity. The U.S. Geological Survey is compiling a set of maps showing thermal maturity of rocks in the sedimentary basins of the onshore conterminous United States. The maps will show three levels of maturity bounded by the 0.6 and 1.3 percent vitrinite reflectance equivalent (VRE) levels, which are generally believed to mark the start and end of significant oil generation. The set will consist of a surface map and maps showing depth contours to the 0.6 and 1.3 VRE boundaries. Some of the areas for which preliminary compilation is complete are the greater Green River Basin, Denver Basin, Piceance Basin, northern Appalachian basin, and Williston basin.

Comparisons of thermal maturity patterns with oil and gas occurrence in these basins show interesting relations. In the Denver Basin, for example, most oil is reservoired in thermally immature sedimentary rocks, implying long-distance migration from deeper parts of the basin. By contrast, in the Appalachian basin, the occurrence of oil and the transition from oil to gas follow closely the 0.6 and 1.3 VRE maturity levels. This latter relation between thermal maturity and oil and gas occurrence fits the classical carbon ratio theory stated in 1915 by David White of the U.S. Geological Survey.

Besides basin-wide mapping of thermal maturity, local detailed knowledge of maturity can contribute to understanding the structure and history of complex thrust belts by identifying anomalous superpositions of contrasting maturities and by showing whether generation of oil occurred when conditions were right to develop economic accumulations.

Thermal maturity, a fundamental property of sedimentary rocks, has wide potential application beyond petroleum exploration and petroleum resource assessment. The importance of organic maturity has long been recognized by the coal industry. The economic value of coal deposits and the technology of coal utilization are directly related to levels of organic maturation (rank). Some types of precious metal and rare element mineralization can be recognized from anomalous patterns of thermal maturity of potential host rocks. Knowledge of regional thermal maturity may refine reconstructions of paleotectonic processes and may improve our understanding of the thermal history and physical state of the lithosphere beneath sedimentary basins.

TRACE-ELEMENT ASSOCIATIONS IN COALS OF THE EASTERN UNITED STATES

Curtis A. Palmer, Paul C. Lyons, and Zoe Ann Brown

Most of the trace elements in coal beds of the Eastern United States are associated with microscopic mineral species that are detrital, syngenetic, or epigenetic in origin. Vitrinite, the major maceral in these coals, may include submicroscopic mineral grains with specific elements which along with organically bound trace elements contribute to the inherent ash of the coals. By comparing the trace-element compositions of vitrinite concentrates with the compositions of the whole coal, one can interpret whether particular trace elements are vitrinite associated or whole-coal associated.

Nine hand-picked vitrinite concentrates, from eight coal fields or basins in Eastern United States, were analyzed for 29 trace elements using instrumental neutron activation. These concentrates represent coal of various ranks from the following areas: one meta-anthracite from the Narragansett Basin (Massachusetts), two anthracites from the folded Appalachians (Pennsylvania, West Virginia), four high-volatile B to low-volatile bituminous coals from the Appalachian Plateaus (Alabama, West Virginia, Maryland) and two high-volatile C bituminous coals from the Illinois Basin (Indiana, Kentucky). The high-temperature (1,000°C) ash contents of these concentrates were 2 percent or less, except for the meta-anthracite, which was 5 percent.

The distribution of rare-earth elements (REE) in the concentrates is distinctly different for the four rank groups (fig. 1). The REE distribution in the meta-anthracite concentrate has a Eu anom-

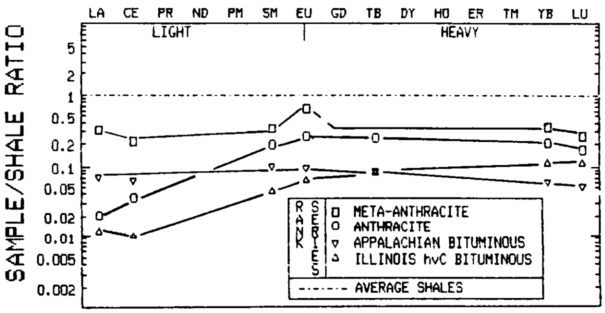


FIGURE 1.—Representative rare-earth concentrations in the four different vitrinite rank groups (average shales from 1966 study by Haskin and others).

aly and is enriched in La. This anomaly may be due to microscopic impurities in the concentrate. The anthracites and the high-volatile C bituminous concentrates have similar distributions that are depleted in lighter REE but have markedly different La:Ce ratios. The depleted light REE distributions may reflect differences in geochemical processes or a different constituent diluting the clastic-shale pattern. The Appalachian bituminous concentrates have relatively flat REE patterns similar to the average shale pattern but slightly depleted in heavy REE. Whether or not these distributions are due to rank or regional differences is not clear.

Significant correlations of Fe, As, and Sb for all concentrates indicate association in pyrite. Other significant correlations (such as K, Hf, Ta, Th, and the REE) suggest that clays and heavy accessory minerals such as phosphates, rutile, and zircon may be present. A comparison of trace elements in the whole coal with those in the vitrinite concentrates indicates that certain trace elements are associated with the organic matrix of the coals.

THE SHUBLIK FORMATION—A MODEL FOR DEPOSITION IN AN ANCIENT MARINE UPWELLING ZONE

Judith Totman Parrish

The Shublik Formation (Triassic, North Slope of Alaska) comprises several lithologic facies that are consistent with deposition in an upwelling zone. These include the following: (1) black, laminated, pyritic limestone; (2) nodular and oolitic phosphorite; and (3) glauconitic sandstone and siltstone. The facies are distributed in east-west-trending belts, with the limestone facies farthest to the south (basinward) and the glauconitic facies farthest to the north (shoreward), where it occurs only in the subsurface. This distribution also is reflected in the vertical succession. Although the facies intertongue, the limestone and glauconite are never interbedded with each other, but both can be interbedded with the phosphorite.

Rocks in the limestone facies contain as much as 6 percent total organic carbon. The high organic carbon content, paucity of bioturbation, presence of pyrite grains and nodules, and relative enrichment in such elements as cobalt, copper, and nickel all suggest that the rocks in this facies were deposited in an anoxic environment. Furthermore, the limestone facies is fossiliferous, containing extremely abundant, very thin shells of pelagic bivalves. The abundance of these shells is evidence for high biologic productivity in the water column overlying the anoxic sediments. Phosphate in the adjacent facies (as much as 14 percent P in the nodules) supports this interpretation. Phosphate indicates a high rate of supply of phosphorus-rich organic matter to the sediment-water interface; in modern upwelling zones, the phosphate is mobilized from the organic matter in the anoxic zone and reprecipitated at the zone's edges. Glauconite in the third facies is indicative of slightly reducing conditions. Glauconite occurs as filling in microfossil tests, glauconitized fecal pellets, grain coatings, and cement. The former two types of grains can result from micro-reducing environments, but the latter two types suggest a reducing environment in the sediment as a whole. Therefore, the lithological and geochemical facies of the Shublik Formation are congruent with a depositional environment in which high biologic productivity created an oxygenation gradient from anoxic in the most highly productive part to slightly dysoxic closer to the shoreline. This interpretation is most consistent with the conditions and sediments found in modern upwelling deposits.

STRUCTURAL DEVELOPMENT OF THE SOUTHEASTERN MARGIN OF THE ANADARKO BASIN, OKLAHOMA

William J. Perry, Jr.

Field investigations in the western Arbuckle Mountains, on the southeastern margin of the Anadarko basin, Oklahoma, show that compressive deformation of Late Mississippian to Pennsylvanian age has played a dominant role in the structural development of the southeastern Anadarko basin, followed in Late Pennsylvanian (Virgilian) time by a modest amount of strike-slip. Both gravity sliding and strike-slip have recently been favored by others to fully explain the structural development of the area. My investigations do not support these hypotheses.

Mesoscopic south-dipping contraction faults and north-vergent concentric folds with associated uplimb thrusts, exposed on the crest and southwestern limb of the Arbuckle anticline south of Turner Falls, Oklahoma, are cut by strike-slip faults associated with the left-lateral Washita Valley fault system. Along the main strand of the Washita Valley fault in the Turner Falls area, a pull-apart graben is filled by Upper Pennsylvanian Collings Ranch Conglomerate. This graben indicates that the strike-slip motion was transtensional and hence not responsible for compressional deformation. Consequently, the Arbuckle anticline does not represent a positive flower structure. The length of the graben appears to constrain the magnitude of strike-slip motion along the Washita Valley fault zone to less than 2 miles. Surface features of left-slip faults of the Washita Valley system and associated antithetic right-slip faults of small displacement indicate that these faults formed subsequent to the growth and erosion of the Arbuckle anticline to near-present erosional levels, which is consistent with the observed cross-cutting relationships.

Early contraction faults and associated minor folds in the Ordovician Viola Limestone on the north limb of the Arbuckle anticline, Lake Classen area, have been passively rotated with the north limb and are *not* evidence of gravity sliding. Locally this limb is overturned and the early deformational features rotated more than 90°.

Farther north, in the Sooner Quarry–SW Davis oil field area, the north-trending Russell fault system displays late right-slip motion superimposed on earlier compressional deformation features associated with the growth of the Russell anticline. More than 90 percent of slip lines observed in slicken-sides on the quarry walls indicate a major component of dip-slip motion.

The mesoscopic deformational features observed require that northeast-southwest compression, rather than strike-slip, has played a dominant role in formation of the Arbuckle anticline and associated oil-producing structures, along a trend that projects westward into the Cement Field area in the deep Anadarko basin. My findings are consistent with the basement-involved thrust origin of the Arbuckle anticline proposed by W. G. Brown, Baylor University, as well as the more complex multistage deformational history proposed by K. C. Nielsen and Q. T. Islam, University of Texas at Dallas. My field data require that strike-slip faulting occurred late in the deformational history of the area, subsequent to the development of the Arbuckle anticline and associated southeastern margin of the Anadarko basin.

BURIAL HISTORY AND TIMING OF THERMAL GAS GENERATION IN CRETACEOUS ROCKS, EASTERN UINTA BASIN, UTAH—EVIDENCE FROM LOPATIN RECONSTRUCTION

Janet K. Pitman and Karen J. Franczyk

Burial reconstruction profiles of Cretaceous and Tertiary sequences in the eastern Uinta Basin, Utah, reveal that major tectonic events, which took place during the Laramide and later periods of epeirogenic uplift and erosion associated with the development of the Colorado Plateau, controlled the thermal evolution and timing of hydrocarbon generation. Upper Cretaceous rocks in the eastern Uinta Basin contain large amounts of nonassociated thermogenic gas trapped in diagenetically modified, low-permeability reservoir sequences. These units are of the same age and origin as other hydrocarbon-bearing rocks that are currently being explored in the Rocky Mountain region; however, little is known about their source potential or generation history. This study applies the Lopatin method to (1) reconstruct the burial history of Cretaceous rocks in the eastern Uinta Basin, (2) evaluate the thermal gradient as a function of time, (3) determine the effect of episodic uplift and erosion on maturation, and (4) establish the time at which gas generation commenced in these rocks.

Studies along the outcrop document that prolonged sedimentation occurred during Late Cretaceous in marine and nonmarine settings along the margin of the Western Interior Cretaceous seaway. In the late Campanian to early Maestrichtian, a regional unconformity that now separates Cretaceous and Tertiary strata across much of the basin developed, as widespread differential ero-

View northward up the Sheridan Glacier from tidewater, Prince William terrane, near Cordova, Alaska. Present TACT seismic-refraction lines extend north from approximately this point some 330 km inland to near the Denali fault in central Alaska. A number of strike lines also have been shot. This location marks southern end of land-based TACT work, but future plans call for seaward extension south into Prince William Sound. Original color slide by D. L. Campbell, August 1985.

sion associated with Laramide tectonism occurred. The amount of section eroded during the Late Cretaceous did not affect the thermal maturity of the remaining Cretaceous rocks because these units were never deeply buried. We have constructed a preliminary burial history model which demonstrates that Cretaceous rocks were thermally immature until the middle Oligocene, when they reached their maximum depth of burial, following the deposition of approximately 7,000 ft of Tertiary sediments. The duration of maximum burial for these Cretaceous rocks (from about 32 to about 17 Ma) was relatively brief, probably less than 15 m.y.; however, during this period thermal generation of gas began and the present level of maturation was attained. Our burial history model indicates that sedimentary burial rather than variations in the temperature regime controlled the thermal maturation of organic matter. The paleogeothermal gradient, estimated at about 1.8°F/100 ft, appears to have been fairly constant from Late Cretaceous through middle Miocene time. Beginning in the Miocene and continuing possibly into the present, the Colorado Plateau along with the Uinta Basin was episodically uplifted and intensely eroded. Widespread unroofing of Tertiary strata through much of the eastern and central part of the basin caused a gradual decrease in the paleogeothermal gradient to the cooler present-day gradient, estimated at about 1.6°F/100 ft. In response to these lower temperatures, the rate of thermal gas generation decreased.

The evolution of the pressure regime in the eastern Uinta Basin may be related to its maturation-generation history. Several studies have attributed high formation pressures in low-permeability rocks to the generation of hydrocarbons from interbedded carbonaceous source rocks. Indirect pressure data from wells recently drilled in the eastern part of the basin indicate that Cretaceous rocks, presently at burial depths of about 9,000 ft, are slightly overpressured. Thus, it is probable that abnormally high pressures may have been widespread in younger Cretaceous rocks when they were at their maximum depth of burial and undergoing peak gas generation. These high formation pressures may have gradually dissipated to normal or subnormal pressures in response to lowered temperatures caused by regional uplift and erosion during the late Tertiary.

USGS MULTICHANNEL SEISMIC-REFLECTION PROFILE 25—A STRATIGRAPHIC REFERENCE SECTION FOR THE BALTIMORE CANYON TROUGH

C. Wylie Poag and John A. Grow

U.S. Geological Survey multichannel seismic-reflection profile 25, which crosses the depocenter of the Baltimore Canyon trough perpendicular to the New Jersey shoreline, serves as the standard stratigraphic reference section for the trough and the contiguous wedge of deep-sea deposits along its eastern margin. Seismostratigraphic interpretations of line 25 and a closely spaced grid of intersecting seismic lines are integrated with lithostratigraphic and biostratigraphic analyses of 50 boreholes to interpret the geologic history of this East Coast region.

Our interpretation of line 25 indicates that more than 20 km of sedimentary strata fills the depocenter of the trough. At the base of this sedimentary column is 5 km of inferred Late Triassic synrift sediments, presumed to comprise chiefly continental deposits, including volcanogenic beds. A major erosional unconformity separates the synrift deposits from overlying postrift sequences. The oldest postrift section consists of 12 km of Jurassic rocks, which range from nonmarine(?) facies near shore to shallow-water carbonate facies along the outer shelf and deepwater carbonates on the Jurassic slope and rise. Evaporitic strata are present as ridges and diapirs within the shelf deposits. An Oxfordian shelf-edge reefal bank is a notable feature and a potential target for petroleum exploration within this Jurassic carbonate regime.

During the Early Cretaceous, sedimentation and subsidence rates diminished; siliciclastic debris buried the shelf-edge reefal bank and terminated widespread carbonate deposition on the shelf, while supplying large quantities of terrigenous detritus to abyssal fans and "black-shale" facies as far as 400 km from the shelf edge. Siliciclastic deposition dominated the remainder of Mesozoic time as rising Late Cretaceous sea levels established marine environments west of the present-day outcrop of Cretaceous strata in New Jersey.

A dominantly carbonate regime was reinstated during the Paleogene, as deepwater biosiliceous chalks, limestones, and calcareous clays accumulated throughout the trough and along its eastern margin. The dominance of carbonate deposition was terminated, however, in the Oligocene, when terrigenous marine sequences again filled the trough. Subsequently, an unusually large delta complex prograded across the shelf in the Miocene, initiating development of what is now the New Jersey continental slope. Since then, chiefly noncarbonate deposition has characterized the trough.

Paleobathymetric cycles and regional unconformities within this trough can be traced from the coastal plain to the upper rise, indicating that sea-level fluctuation in concert with basin subsidence played a major role in determining the depositional fabric of the trough and its seaward margin. Depositional sequences on the shelf have equivalents on the slope and rise, and correspond remarkably well with supercycles of the controversial Vail depositional model.

Postrift tectonic movement has been chiefly long term subsidence brought about by lithospheric cooling and sediment loading. These processes produced several large growth faults and an elongate, faulted anticlinal structure, which form potential petroleum traps along the eastern edge of the trough.

PETROLEUM GENERATION AND MIGRATION IN LOWER JURASSIC LACUSTRINE SEQUENCES, HARTFORD BASIN, CONNECTICUT AND MASSACHUSETTS

Lisa M. Pratt, April K. Vuletich, and Robert C. Burruss

The Hartford basin in Connecticut and Massachusetts is one of a series of elongate fault-bounded basins along the eastern margin of North America that contain Triassic and Jurassic sedimentary rocks. Nonmarine deposits and basalt flows in the Hartford basin total about 4 km in thickness, and some units can be correlated for 140 km along the length of the basin. Deep-water lacustrine sequences typified by lithologic cycles of (1) gray silty mudstone, (2) black laminated shale, and (3) gray silty mudstone are well developed in the Lower Jurassic Shuttle Meadow and East Berlin Formations. Crossbedded channel sandstones, red flood-plain mudstones, and ripple-marked lacustrine siltstones were deposited during dry periods between times of development of extensive perennial lakes.

In order to evaluate the thermal history and petroleum potential of the Hartford basin, outcrop samples were collected from localities spanning the north-south extent of the basin. Organic-carbon content, Rock-Eval pyrolysis yield, and carbon isotope ratio of organic matter were determined for 66 samples of medium-gray to black shale and siltstone. Amount and character of extractable organic matter were determined for ten representative shale samples, one "solid" bitumen intermingled with calcite spar from a joint in the Lower Jurassic Holyoke Basalt, and one "sticky" bitumen from the core of a cylindrical concretion in the East Berlin Formation.

Temperatures of maximum pyrolytic yield (T_{max}) and hydrogen indices (HI) of the black lacustrine shales (organic-carbon content = 0.9 to 3.8 weight percent) indicate sharply decreasing thermal maturity from north to south in the Hartford basin. T_{max} values are greater than 450°C and HI values are less than 50 mg/g in Massachusetts and northern Connecticut. Correlative shales in central and southern Connecticut generally have T_{max} values between 425° and 436° and HI values between 150 and 280 mg/g. Scattered localities in Connecticut have anomalously high thermal indices, but most localities are marginally mature to mature with respect to petroleum generation.

Extraction yields are 1,800 to 3,100 ppm for the black lacustrine shales. The n-alkanes have a smooth distribution with a maximum between n-C_{17} and n-C_{19}. Pristane/phytane ratios are about 1.6. The distribution of n-alkanes and biomarkers in the extractable portion of the "solid" bitumen from the Holyoke Basalt is indistinguishable from that of the shale extracts. The extractable portion of the "sticky" bitumen contains n-alkanes with slight even-carbon predominance from n-C_{18} to n-C_{24}, but the distribution of biomarkers is similar to that of the shale extracts. Two-phase, liquid and vapor fluid inclusions in cements adjacent to both types of bitumen contain brightly fluorescent hydrocarbons.

Organic geochemical analyses of surface samples indicate that the Shuttle Meadow and East Berlin Formations are moderate to good oil source rocks in the central and southern portions of the Hartford basin. These same rocks in the northern portion of the Hartford basin are overmature with respect to oil generation and occurrence, but may be source rocks for gas. The cumulative thickness (8–10 m) of widespread possible source rocks should be adequate for commercial petroleum accumulation. Extensive faulting and the large area of contact between potential source beds and adjacent siltstones and sandstones may have enabled efficient expulsion and migration of hydrocarbons. The presence of hydrocarbon liquids in fluid inclusions demonstrates at least local generation and migration of petroleum in the Hartford basin.

MAGNETIC MINERALS AND HYDROCARBON SEEPAGE—POSSIBILITIES FOR MAGNETIC DETECTION OF OIL FIELDS

Richard L. Reynolds, Neil S. Fishman, Mark R. Hudson, J. A. Karachewski, and Martin B. Goldhaber

Aeromagnetic anomalies detected over some oil fields in the Anadarko basin (Oklahoma) and on the North Slope (Alaska) have been attributed to near-surface diagenetic magnetite formed in the presence of migrated hydrocarbons. If magnetite or other magnetic minerals result from hydrocarbon seepage, aeromagnetic techniques offer a promising complement to conventional exploration methods. Rock magnetic, paleomagnetic, and geochemical studies have been undertaken to test models of magnetite diagenesis related to hydrocarbon seepage and to investigate the sources of magnetic anomalies over the Cement oil field (Anadarko basin, Oklahoma), the Simpson oil field (North Slope, Alaska), and the Wyoming-Idaho-Utah thrust belt.

Magnetite, reported previously in well cuttings from the Cement field, commonly exhibits synthetic textures and contains inclusions of industrial iron. The magnetite, thus, is a contaminant that probably was introduced during drilling. Ferrimagnetic pyrrhotite (Fe_7S_8), however, occurs at shallow depths (≈70 to 300 m) above oil-producing strata, and it may contribute to aeromagnetic anomalies over the Cement field. The limited areal distribution of the pyrrhotite and the closely similar sulfur isotopic compositions of the pyrrhotite (–2.0 to +9.9 per mil) and of underlying crude oils (+1.8 to +7.3 per mil) suggest that pyrrhotite formed from aqueous sulfide in hydrocarbon-bearing brines that migrated toward the surface along numerous faults in the area.

At the Simpson oil field, greigite (Fe_3S_4), another authigenic ferrimagnetic iron sulfide mineral, is concentrated locally in Upper Cretaceous mudstone and sandstone. Highest values of magnetic susceptibility and intensity of natural remanent magnetization (NRM) in unoriented core samples correspond to zones of greigite enrichment. Greigite thus may be the dominant source of magnetic anomalies over the field, but some contribution from detrital iron-titanium oxide minerals, principally titanohematite, is possible. The greigite formed via processes involving sulfate-reduction by bacteria that used either detrital organic matter or migrated hydrocarbons as a food source.

In the Wyoming-Idaho-Utah thrust belt, the Jurassic Preuss Formation has magnetizations as much as 0.76 amperes/meter (average 0.14 A/m) west of the Absaroka thrust fault, where aeromagnetic anomalies locally correspond to exposures of the Preuss, and much lower magnetizations (average 0.44×10^{-2} A/m) east of the Absaroka fault. The magnetization is carried by large (10 to 80 μm diameter), rounded, titanium-bearing detrital magnetite, commonly concentrated along heavy mineral laminations. Visible diagenetic magnetite has not been found, and the presence of submicroscopic diagenetic magnetite is very unlikely, on the basis of a linear relation between site-mean values of magnetic susceptibility and NRM intensity. Carbon isotopic compositions of calcite cement (–2.4 to +1.5 per mil) do not indicate that hydrocarbons influenced the preservation of the detrital magnetite.

Diagenetic magnetite is not the source of magnetic anomalies associated with the Cement and Simpson oil fields or with the Preuss Formation. At each area, instead, a different authigenic magnetic mineral has formed, or a detrital mineral has been preserved, under vastly different geochemical conditions. A complete evaluation of aeromagnetic methods in locating hydrocarbon deposits should include study of different geochemical and structural settings to distinguish authigenic (or detrital) magnetic minerals formed (or preserved) under the influence of hydrocarbons from magnetic phases that are unrelated to seepage.

NANUSHUK GROUP COAL INVESTIGATIONS— NORTH SLOPE OF ALASKA

E. G. Sable, G. D. Stricker, and R. H. Affolter

The North Slope of Alaska contains vast resources of virtually undeveloped coal, much of which occurs within mineable depths. The main coal-bearing units, the Corwin and Chandler Formations of the Lower and Upper Cretaceous Nanushuk Group, underlie more than 25,000 mi^2 (64,750 km^2) of the North Slope. They contain low-sulfur, low-ash, subbituminous, and coking-quality bituminous coal in gently dipping beds as thick as 20 ft (6.1 m), within stratigraphic intervals as thick as 10,000 ft (3,050 m). Coal resources of lesser quality and quantity also occur in other Upper Cretaceous, Lower Mississippian, and Tertiary rocks.

The river-dominated, in part coeval, Corwin and Umiat deltas controlled the distribution of Nanushuk Group coal-forming environments. The larger Corwin delta (Corwin Formation), in the western part of the North Slope, prograded northeastward and eastward; the smaller Umiat delta (Chandler Formation), in the central part, prograded northward. Most organic deposits formed on delta plains; others formed in alluvial-plain or delta-front environments. Most North Slope coal beds are lenticular and irregular, probably due to accumulation in interdistributary basins, infilled bays, or inland flood basins. Some widespread tabular beds that formed on wide, slowly sinking delta lobes may also be present. The major controls of coal rank and degree of deformation were depth of burial and subsequent tectonism.

Since 1975, ninety-six coal samples from the Corwin and Chandler Formations have been analyzed in order to evaluate coal quality and element distribution. Their apparent rank ranges from lignite A in undeformed strata to high-volatile A bituminous in moderately deformed units.

Coal from the North Slope is significantly lower in ash, volatile matter, O, Si, Al, Ca, Fe, Ti, Cu, F, Li, Mn, Mo, Pb, Sb, Se, Th, and Zn than Cretaceous coal of the western conterminous United States. Sulfur values are as low as 0.1 percent, and elements that normally show a positive correlation with sulfur are also low. Variations in element content probably reflect geochemical differences in the Corwin and Umiat delta systems.

Nanushuk Group hypothetical coal resources on the North Slope are estimated to be 3.1 trillion short tons. This value is the sum of 1.8 trillion tons of near-surface (<500 ft (150 m) of overburden) bituminous coal, 1.24 trillion tons of near-surface subbituminous coal to lignite A, and 0.06 trillion tons of more deeply buried subbituminous coal. Of the total, roughly 2.53 trillion tons of coal occurs in beds having less than 15° dip. These estimates indicate that the North Slope of Alaska may contain as much as one-third of the United States coal resources.

Information about North Slope coal is scant compared to major coal-producing areas in the conterminous United States: the Powder River Basin, for example, contains more than 5,000 test wells, whereas North Slope coal information is available from less than 50 test wells. A systematic drilling program is needed to develop more accurate resource estimates and increase the currently sparse and mostly localized information on quality and geochemistry of North Slope coals.

THE SALTON SEA SCIENTIFIC DRILLING PROGRAM—A PROGRESS REPORT

J. H. Sass, J. D. Hendricks, S. S. Priest, and L. C. Robison

One of the first major experiments of the U.S. Continental Scientific Drilling Program is being carried out in the Imperial Valley of California, as the Salton Sea Scientific Drilling Program (SSSDP). The research well is situated near the southeast end of the Salton Sea in the Salton trough, a tectonic depression within the transition zone between the spreading centers of the Gulf of California and the San Andreas transform fault. The trough is a fluvial sedimentary basin with associated evaporitic and lacustrine deposits. Within it high temperatures (up to 370°C at only 2 km depth) and hypersaline brines (up to 250,000 ppm total dissolved solids) are encountered. The drill site is near the hottest part of the Salton Sea Geothermal Field as deduced from temperatures in previously drilled deep wells and temperatures extrapolated from shallow (≈50–100 m) wells. The well is being drilled using standard technology, but it is different from conventional exploration or production wells in a number of ways, chief among which is the priority of scientific over economic objectives. The primary goals are to study the processes involved in an active, magmatically driven hydrothermal system. The temperatures, pressures, and salinities in the well provide an opportunity for the evaluation of geothermal energy potential and a convenient laboratory for the study of greenschist metamorphism and hydrothermal ore formation in place.

To facilitate the studies of these active processes, the SSSDP has attempted to maximize data collection in four areas: (1) core recovery, (2) geophysical logs, (3) downhole experiments, and (4) sampling of formation fluids. The extent of all these activities is limited by the hostile environment encountered in the research well. Some procedures routinely available in more benign regimes (such as open-hole packer tests, in-place stress measurements, and gun-perforation) are not technologically feasible in the Salton Sea experiment.

The science experiments fall into three major categories: downhole, surface, and off-site. In the first category we shall attempt to obtain a detailed equilibrium temperature profile by a time-series of continuous temperature logs during the post-drilling idle period. This profile will provide information vital to the interpretation of virtually all other data obtained from the well. Other downhole experiments include fluid sampling, temperature-pressure-flow measurements during flow tests, vertical seismic profiling, and borehole gravity and fracture studies using acoustic logging and borehole televiewers. Surface experiments are primarily thermodynamic measurements and the collection of fluid samples during flow tests. Off-site experiments deal with description, analysis, and measurement of fluid and core samples obtained during drilling. The major subdivisions within this latter group include the chemistry of liquids and gases and the petrology, geochemistry, and physical properties of core samples.

At the conclusion of the post-drilling shut-in phase (about 6 months duration) a number of options will arise for further work. If flow tests during and immediately after drilling are encouraging, support will be sought for studies aimed at a systematic reservoir evaluation. The leaseholder (Kennecott) may opt to take over the well as a commercial venture. If neither of these options is exercised, the well will be plugged and abandoned at the conclusion of the shut-in period.

The new data from SSSDP should result in refined models for the Salton Sea system, improve assessment of its geothermal energy potential, and provide important constraints on models of metamorphism and ore formation. The project should also fulfill scientific and organizational goals by providing guidelines for future continental scientific drilling experiments.

CLASSIFICATION OF CLASTIC RESERVOIRS FOR ENHANCED OIL RECOVERY

C. J. Schenk, J. W. Schmoker, and D. L. Gautier

Enhanced oil recovery (EOR) encompasses a number of processes to chemically or thermally stimulate petroleum reservoirs to produce a portion of the oil remaining after primary and secondary recovery. Several hundred reservoirs in the United States are amenable to EOR processes. The purpose of this study is to assign reservoirs to generic classes, or populations, in order to determine which reservoirs should have precedence for EOR, and to provide a geologic data base that will aid selection of EOR processes.

Reservoirs in clastic rocks can be described and classified in terms of facies, each of which has a set of primary sedimentologic, mineralogic, and petrophysical attributes. Potential EOR reservoirs will be grouped into populations based on similarity of facies. Each facies may include, or be separated by, impermeable mudstone layers that persist through burial, and which probably represent the most important control on fluid flow through a reservoir. The identification of these permeability barriers, and descriptions of their lateral extent and distribution, will be an important aspect in defining classes of reservoirs.

The primary textures, mineralogies, and petrophysical parameters in each facies typically undergo diagenetic changes during burial that can significantly affect fluid flow in the reservoir. Changes in these reservoir properties during burial are a complex function of the primary mineralogy of a sandstone, the composition of any fluids that have passed through a sandstone, and the time-temperature exposure of the reservoir. The changes in reservoir properties among sandstones of similar primary mineralogies depend exponentially on temperature, and linearly on time, and may be systematized and predicted in terms of the reservoir time-temperature exposure. The time-temperature index of thermal maturity (TTI) is used as one convenient measure of time-temperature exposure.

Using the populations of reservoirs as a starting point, the effects of burial processes upon reservoir properties will be the basis for defining sub-populations based on other characteristics, such as fractures, authigenic mineralization, or hydrocarbon type. Identification of sub-populations based on these and other characteristics may be useful in decisions regarding the choice of EOR procedure.

WINDOWS IN THE PULASKI THRUST SHEET AND THEIR IMPLICATIONS FOR HYDROCARBON POTENTIAL ALONG THE EASTERN PART OF THE APPALACHIAN OVERTHRUST PROVINCE

Arthur P. Schultz and Donald E. Anders

Highly deformed Cambrian through Devonian rocks are exposed in windows in the Pulaski thrust sheet of the Virginia Valley and Ridge structural province near the southern-central Appalachian junction zone. Detailed mapping of these exposures shows a consistency of structural style, namely, faulted and stacked antiforms with duplex geometry and folded roof thrusts. Strain intensity and the style of regional folds and faults suggest that the windows are shurflingsfensters which expose rootless, tectonic slices, or horses. Structural analyses of these rocks show that in thick-bedded carbonates and sandstones, cataclasis was the dominant deformation. By contrast, thin-bedded shales, sandstones, and limestones were isoclinally folded, cleaved, and boudinaged. Tectonic thinning and strain intensity in the horses are dependent on the distance of transport from their root zone, which may be a ramp in the trailing part of the subjacent Saltville thrust sheet. A 1982 interpretation by Leonard Harris and others of the U.S Geological Survey's central Virginia seismic line places this ramp east of and below the crystalline rocks of the Blue Ridge province. Geometric modeling of rocks in the windows supports this interpretation and suggests the existence of possible Cambrian through Mississippian hydrocarbon-bearing rocks below the Blue Ridge thrust sheet.

View northward from near head of Schwan Glacier on south flank of Cordova Peak, Chugach terrane, Alaska. For TACT seismic-refraction study, seismometers were deployed by helicopter at approximately 1-km spacing along a due-north line that extends up left side of glacier. Original color slide by D. L. Campbell, August 1985.

Rock samples from the horses were collected to determine thermal maturity and source-rock potential. Preliminary results indicate that Devonian and Ordovician black shales in the windows could have been source rocks but that their present overmature condition probably indicates a low hydrocarbon potential for Paleozoic rocks below the eastern part of the Blue Ridge province. However, if the rootless slices overlie Paleozoic rocks of more western affinities, the maturation level in the slices is not indicative of the maturation levels in the overridden rocks. Consequently the hydrocarbon potential of rocks below the Pulaski and subsidiary Max Meadows thrust sheets and below the western part of the Blue Ridge province has yet to be determined.

LOW-ASH SYNTHETIC FUEL FROM LIGNITE, PEAT, OR SEWAGE SLUDGE

Frank E. Senftle and Priscilla I. Hackney[6]

The United States has large tonnages of lignite and peat that are considered unsuitable for fuel application. Concurrently, municipal governments in many areas of the world are facing an ever-increasing problem of the disposal of sewage sludge—a high-ash renewable carbon source. If the organic part of these carbon sources could be put into aqueous solution and reconstituted as a low-ash solid, a product might be obtained which

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FIGURE 1.—Photograph of polymer produced from sewage sludge. Typical values: Heating value 28 MJ/kg (megajoules per kilogram) (1.2×10^4 Btu/lb), sulfur ≈ 2 percent, and ash ≤ 4 percent.

would be suitable as a fuel or a source material for producing organic chemicals.

Petroleum chemists have long known that aliphatic and certain aromatic compounds form esters when reacted with concentrated H_2SO_4. In the presence of isoparaffinic compounds, these esters react further to form a polymer and sulfuric acid. The acid therefore functions as a catalyst. Similar chemical procedures can be used with peat, lignite, and sewage sludge to extract the organic fraction. The extracted organic fraction after polymerization could be separated as a solid fuel.

Preliminary experiments have been made on peat, lignite, and sewage sludge. A photograph of a solid polymer formed from sewage sludge is shown in figure 1, and typical values of sulfur, ash, and heating value are given in the caption.

GEOTHERMAL SYSTEMS IN THE CASCADE RANGE

Michael L. Sorey, Steven E. Ingebritsen, and Robert H. Mariner

The Cascade Range is a 1,200-km-long belt of Quaternary volcanic terrane punctuated by several stratovolcanoes; it represents the only subduction-related volcanic arc in the conterminous United States. Magmatic heat sources within this range that could drive high-temperature geothermal systems are indicated by concentrations of Holocene silicic volcanic rocks at six eruptive centers and by regions of high regional heat flow that underlie most of the Cascade Range in Oregon. High-temperature geothermal systems have been identified at Meager Mountain (British Columbia), Newberry Volcano (Oregon), and Lassen Volcanic National Park (California), and exploration for similar systems is currently in progress by private industry at Medicine Lake Volcano (California) and Crater Lake (Oregon).

Three general types of geothermal systems can be delineated within the Cascade Range—summit crater systems, caldera systems, and regional flow systems. Summit-crater systems occur at Mount Shasta, Mount Hood, and several other of the andesite-dacite composite volcanoes that display persistent fumaroles or hot springs. Although gas geothermometry yields estimates of subsurface temperature in excess of 200°C at Mount Shasta and Mount Hood, hydrothermal circulation in these systems appears to be confined to shallow depths within the summit craters and to downdip flow of heated ground water or steam condensate to warm springs along the flanks of the volcanoes.

Caldera geothermal systems at Newberry, Medicine Lake, and Crater Lake appear to include zones of relatively deep fluid circulation along ring fractures. Test drilling by the U.S. Geological Survey at Newberry has provided evidence that permeable strata containing water at temperatures near 265°C exist within the volcanic section at depths of 1–2 km. Although these caldera systems may offer the greatest likelihood of high-temperature geothermal resources within the Cascade Range, geothermal exploration at Crater Lake and Newberry is currently restricted to regions surrounding the calderas.

A regional flow system occurs at Lassen Volcanic National Park and in the Known Geothermal Resource Area to the south. It includes a central vapor-dominated zone at temperatures near 240°C that feeds steam to superheated fumaroles within the park. Hot water that upwells beneath this zone boils, and the liquid fraction flows laterally away from the park, eventually to discharge in hot springs at lower elevations some 10–15 km away. Exploration for geothermal resources at Lassen is focused on these zones of lateral outflow south of the park.

Geothermal systems associated with hot springs located along the High Cascade–Western Cascade boundary in Oregon also may be regional in scale. Heat flow measurements, stable isotope relationships, geothermometer calculations, and results from a 2.5-km-deep drill hole fit a conceptual model involving circulation of meteoric water westward from the High Cascade axis at depths of 3 km and temperatures of 150°–180°C, and upflow along the edge of the graben within which the High Cascade volcanic rocks have been emplaced. The amounts of chloride contributed by the hot springs to nearby streams require discharge rates for individual systems that range from 1.1 to 110 L/s. Heat required to raise the temperature of this water to 150°–180°C could come from the regional heat flow (100 mW/m^2 (milliwatts per square meter)) for all but one of the spring systems. Additional heating might be related to shallow magmatic sources beneath the High Cascade axis.

THE FORMATION AND ALTERATION OF TABULAR-TYPE URANIUM-VANADIUM DEPOSITS AS A VARIANT OF NORMAL DIAGENETIC PROCESSES IN ORGANIC-RICH SEDIMENTS

Charles S. Spirakis and Paula L. Hansley

Tabular-type uranium-vanadium deposits in the Grants uranium region of New Mexico, the Uravan mineral belt of Colorado and Utah, and the

Henry Mountains mineral belt of Utah occur in fluvial sandstones of the Morrison Formation (Upper Jurassic) and exhibit similar geometry, mineralogy, and alteration. They differ strikingly, however, in the dominance of epigenetically introduced, pore-filling organic matter in the Grants ores in contrast to pore-filling authigenic chlorite in the Uravan and Henry Mountains deposits. Remnant traces of introduced organic matter, the fact that organic matter must be present to reduce uranium, sulfur and other elements in the ores, and uniquely etched garnets in ore-bearing horizons are evidence of previously greater abundances of introduced organic matter in the Henry Mountains and Uravan deposits. In the Henry Mountains, the association of ^{13}C-enriched dolomite with the ores (described by H. R. Northrop in a 1982 study) and the destruction of detrital iron-titanium oxides in and around the ore zones provide additional evidence that greater amounts of organic matter previously existed than are now present. In the Grants region, gradations from organic-rich to chlorite- and coffinite-rich deposits and inclusions of carbon in coffinite indicate that chlorite and coffinite replaced introduced organic matter. We propose that this replacement proceeded further in the Henry Mountains and Uravan areas than in most of the Grants region and that the deposits have a similar genesis. Thus it is appropriate to combine information from these three areas to form a genetic model.

Shortly after sedimentation, organic acid-bearing solutions migrated through the sandstones, altered detrital iron-titanium oxides, transported trivalent vanadium liberated from the iron-titanium oxides, and finally deposited organic matter as tabular bodies in the host sandstones (processes from a 1985 study by C. E. Turner-Peterson and N. S. Fishman). As is typical of early diagenesis, bacteria catalyzed sulfate reduction by organic matter to produce pyrite. Concomitant with sulfate reduction was the precipitation of reduced uranium minerals and of ore-stage chlorite. Upon the exhaustion of sulfate in the sediments, fermentation of organic matter (also typical of early diagenesis) dominated the diagenetic chemistry. Because dolomite, especially ^{13}C-enriched dolomite, is characteristic of the fermentation stage of diagenesis, and because sulfate in the ore stage inhibits the precipitation of dolomite, dolomite associated with the Henry Mountains deposits is concluded to represent the fermentation stage of diagenesis; ankerite in the Grants region also formed after sulfate reduction and may be paragenetically equivalent to dolomite in the Henry Mountains area. Dolomite continued to form until the thermal limit of bacteria was reached (about 75°C or perhaps lower due to possible toxic effects of the ore elements on bacteria). Then, in the ensuing absence of bacteria that metabolize organic acids, organic acids derived from the maturation of organic matter became important components of the solutions that produced the etching of garnets throughout the Henry Mountains and Uravan areas and in parts of the Grants region. The coincidence in space of the garnet etching with the replacement of organics by late-stage chlorite and coffinite indicates that all these alterations are related to the maturation of organic matter associated with the ores.

GEOCHEMICAL CHARACTERIZATION OF SELECTED COALS FROM THE BELUGA ENERGY RESOURCE AREA, SOUTH-CENTRAL ALASKA: SITE OF A PROPOSED COAL MINE

Gary D. Stricker, Ronald H. Affolter, and Michael E. Brownfield

The Tertiary Kenai Group of the upper Cook Inlet region, south-central Alaska, is a nonmarine sedimentary sequence, as thick as 8,000 m. It consists, in ascending order, of the Hemlock Conglomerate, Tyonek Formation, Beluga Formation, and Sterling Formation. All the units are coal bearing, but the thickest beds are found in the Tyonek Formation of early Oligocene to middle Miocene age. This formation is a 1,160- to 2,750-m-thick sequence of massive sandstones, siltstones, and claystones with interbeds of thick coal and a minor number of tuffs(?) and tonsteins. The Tyonek Formation is believed to have accumulated in poorly drained alluvial lowlands adjacent to tectonically active highlands containing sporadically active volcanoes.

The Beluga energy resource area is approximately 90 km west of Anchorage in the upper Cook Inlet region. This area contains over 1 billion short tons of coal resources in the Tyonek Formation alone. The area is tentatively scheduled for coal production beginning in the early 1990's. For baseline data 43 samples representing eight coal beds (Capps, Waterfall, M, O, Q, and three unnamed beds), were analyzed from four U.S. Geological Survey drill holes. Statistical summaries of proximate and ultimate analyses, heat-of-combustion, forms-of-sulfur, and 40 major, minor, and trace elements were compiled and evaluated, along with the mineralogy of the low-temperature ash for each sample. Analyses show an apparent coal rank that ranges from subbituminous B to subbituminous C, with a variable ash content of 4.7 to 46.5 percent. Total sulfur ranges from 0.08 to 0.33 percent, one of the lowest reported total sulfur ranges for any United States coal.

Concentrations of Si, Al, K, Ti, Be, Cr, Cu, F, Ga, La, Li, Sc, Th, U, V, Y, Yb, and Zr show a variation in concentration that is directly related to the ash content of the coal; linear correlation coefficients are greater than 0.8. The M bed has the lowest ash content as well as the lowest concentration of ash correlated elements, whereas the Capps coal bed has a relatively higher ash content and therefore, a higher concentration of these elements. The variability of ash content is probably a direct result of the proximity of the original peat swamp to nearby tectonically active highlands and the episodic nature and varying composition of the adjacent highland's volcanic eruptions.

Mineral analysis of the low-temperature ash reveals a predominance of kaolinite with minor mica-type clays and a varying amount of quartz. X-ray diffraction of selected coal samples indicates the presence of the hydrated alumino-phosphate mineral goyazite ($SrAl_3(PO_4)(OH_5)\cdot H_2O$), which is the strontium end member of the solid-solution plumbogummite series. The presence of this mineral is further supported by chemical analyses of the whole coal, which indicate unusually high concentrations of strontium (1,430 ppm) and phosphorus (4,100 ppm). Previous studies of the minerals of the plumbogummite series report the minerals occurring in altered nonmarine tuffs, which suggests that goyazite in the Tyonek Formation coals probably formed during early diagenesis of air-fall volcanic ash that landed in the peat accumulating swamps.

RESERVOIR FLUIDS OF THE BACA, NEW MEXICO, GEOTHERMAL FIELD

A. H. Truesdell and C. J. Janik

At the Baca geothermal field in the Valles caldera, New Mexico, 19 deep wells were drilled in an attempt to develop a 50-MW power plant. The chemical and isotopic compositions of steam and water samples from wells of the Baca field have been used to indicate uniquely the origin of reservoir fluids and natural reservoir processes. Two distinct reservoir fluids exist at Baca. These fluids originate from the same deep, high-temperature (335°C), saline (2,500 mg/kg Cl) parent water, but have had different histories during upflow (fig. 1).

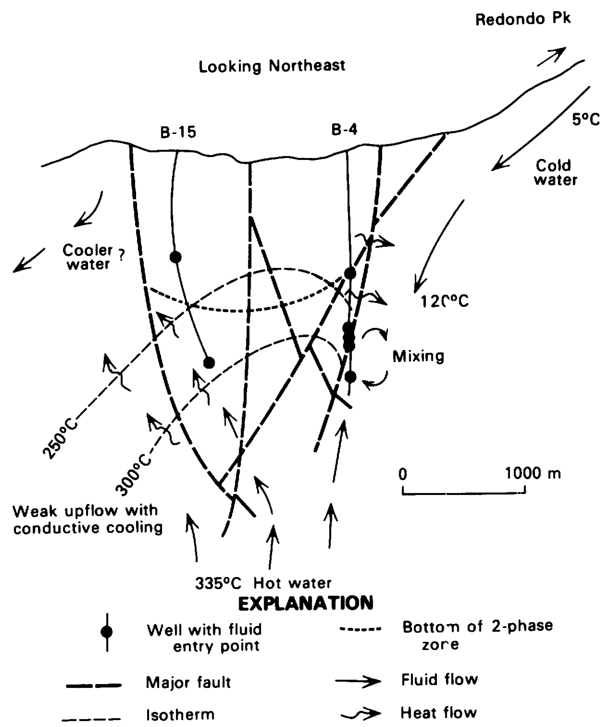

FIGURE 1.—Cross section of the Baca geothermal field (view to northeast) showing deep 335°C upflow mixing with cold water to feed well B–4 and cooling conductively to feed well B–15. No vertical exaggeration.

One fluid (from wells on the east side of the field) is isotopically light, high in radiogenic noble gases, CO_2 and HCO_3, and low in Ca. It has a temperature of 290°–295°C and a reservoir chloride near 1,900 mg/kg. This fluid resulted from rapid upward flow through the 1.1–1.4-m.y.-old Bandelier Tuff reservoir rocks, after long residence in pre-Bandelier (>7 m.y.) sediments and Precambrian basement rocks, and 25 percent dilution with high-altitude cold ground water from Redondo Peak (fig. 1). The other water (from the western wells) moved slowly through the Bandelier Tuff and cooled conductively (with minor steam loss) from 335°C to 280°–260°C. Apparently, short residence in old basement rocks has left this water with low radiogenic gases. Conductive cooling without mixing has kept the original chloride and relatively heavy isotope composition of the deep water. The recharge to the deep parent water is not well understood but may be from lower elevation precipitation outside the Valles caldera area. Pressures of O_2 and S_2 are controlled by mineral assemblages within the Bandelier Tuff. Gases are in equilibrium in all-liquid reservoir fluid at near reservoir temperatures and the concentrations of atmospheric gases are similar to those of air-saturated water, indicating little boiling and steam loss.

All water, solutes, and gases in the reservoir fluids originate from air-saturated meteoric recharge water, water-mineral reactions, and rock leaching, with the possible exception of excess ^3He that must have an ultimate mantle source. This gas could originate directly from magma or from deep leaching of intrusive volcanic rocks beneath the Bandelier.

Chemistry of the Baca well fluids shows that natural reservoir processes are dominated in the west by slow upward fluid movement and conductive cooling, and in the east by rapid upflow and mixing with cold water. The two parts of the reservoir are poorly connected. These processes suggest that under exploitation, western wells will have low permeability and will be poor producers, and eastern wells may show cold water ingress. Neither condition is favorable for long-term electrical production.

URANIUM ORE GENESIS IN THE CONTEXT OF BASIN EVOLUTION, SAN JUAN BASIN, NEW MEXICO

Christine E. Turner-Peterson and Neil S. Fishman

A basin analysis approach was used to understand uranium mineralization in the fluvial-lacustrine Jurassic Morrison Formation, San Juan Basin, New Mexico. Although distribution of uranium ore is areally and stratigraphically restricted, it was necessary, in order to develop a model for ore genesis, to understand the depositional setting of the entire Morrison Formation and to determine the role of depositional setting on hydrology and diagenesis. As a result, we not only understand uranium ore genesis in the San Juan Basin but also have gained insight into processes that have application to the study of other commodities in sedimentary basins.

The Late Jurassic plate tectonic setting of the San Juan Basin was integral to ore genesis. Uplift in a magmatic arc region several hundred kilometers west of the paleo-basin established stream gradients necessary to deliver detritus to the subsiding basin, resulting in deposition of the host sandstones (Westwater Canyon Member and Jackpile sandstone of economic usage). Volcanism in the arc region also supplied abundant volcanic ash throughout Morrison deposition. Alteration of this air-fall ash in a saline-alkaline lake (Brushy Basin Member) was a key element in controlling pore-water composition in the Morrison Formation.

Ore occurs as a pore-filling urano-organic mixture in host sandstones; the organic material is the main ore control. Petrographic evidence reveals that the organic material was introduced into the host sandstones soon after deposition. Reconstruction of burial history indicates that the time of mineralization (Late Jurassic–Early Cretaceous) was not a time of oil generation. These timing constraints, together with chemical studies and alteration patterns, indicate that the organic material in ore zones was a humic derivative. The source of this organic material is the main concern in ore genesis.

Our understanding of the depositional environment of the Brushy Basin Member constrained reconstructions of paleo-basin geometry and also explained ore-related alteration patterns in Morrison sandstones; these alteration patterns, in turn, aided in reconstructing ore-related hydrology and pointed to a source for the organic material. The paleo-basin geometry can be accurately inferred because saline-alkaline lakes develop only in closed-basin settings and because mapping authigenic mineral facies in the lake sediments defines the paleo-lake basin. Our reconstructions indicate that the paleo-San Juan Basin, as defined by the paleo-lake, extended well north of the present-day margin. Pore water that descended from these paleo-lake sediments altered underlying sandstones, and lateral trends in these mappable altered areas parallel the lateral changes in authigenic mineral facies observed in the overlying lake sediments. Detrital feldspar, magnetite, and ilmenite grains in the host sandstones reflect this downward movement of pore fluids. Magnetite and ilmenite grains are of particular interest because their alteration can be directly related to movement of organic-bearing fluids; detailed mapping of these altered mineral grains points to the mudflat facies of the Brushy Basin Member as the source of these fluids. For this reason, ore is restricted to sandstones that received pore fluids from the mudflat facies.

In terms of the hydrologic history of the basin, formation of this organic-rich ore is related to early pore-water evolution in a compacting paleobasin (Late Jurassic–Early Cretaceous), whereas later redistribution into roll-type uranium ore occurred when oxygenated ground water recharged the uplifted basin margin in the Tertiary (post-Laramide), when compaction was largely completed. Radiometric dates indicate that this redistribution process continues to the present day. Thus, evolution of the San Juan Basin, from deposition of the Morrison Formation to the present, was considered in our basin analysis approach to ore genesis.

EVOLUTION OF OIL-SHALE BASINS—EVIDENCE FROM SULFUR GEOCHEMISTRY

M. L. Tuttle and M. B. Goldhaber

The abundance and isotopic composition of major forms of sulfur, together with the sulfide-mineral morphology and paragenesis, were determined for samples of oil shale-rich Green River Formation (Eocene). Our samples came from the Green River basin (GRB), Wyoming; the Uinta basin (UB), Utah; and the Piceance basin (PB), Colorado, from rocks originally deposited as sediment in ancient lake Gosiute (GRB) and in two distinct sub-basins in ancient lake Uinta (UB, PB). We analyzed organic matter (C_{org}), iron (Fe_2O_3), total sulfur (S_{tot}), pyritic sulfur (S_{py}), and organically-bound sulfur (S_{org}), along with the average isotopic composition of the S_{py} and S_{org}, in order to determine the evolution of fine-scale biogeochemical and geochemical changes occurring in the three basins during three lake stages (early, fresh-water; intermediate, saline-water; and late, fresh-water). The results of our analyses are as follows, with values reported as mean abundances and isotopic compositions.

Basin	C_{org}	Fe_2O_3	S_{tot}	S_{py}	S_{org}	$\delta^{34}S_{py}$	$\delta^{34}S_{org}$
	pct						
GRB	3.4	3.0	0.82	0.60	0.08	23.4	23.8
PB	9.8	3.1	1.2	.94	.20	26.2	25.2
UB	5.0	4.2	.84	.50	.11	25.4	28.2

Samples from the three basins contain similar mean sulfur abundances and have similar mean sulfur-isotopic compositions, suggesting that sedimentary-geochemical processes were generally similar between the two lake systems. Slight but systematic differences in the sulfur, organic carbon, and iron data from the UB and PB do, however, suggest that depositional conditions were not uniform within lake Uinta. In addition, the evolution of the sedimentary sulfur was different in lakes Gosiute and Uinta: isotopic values in samples from UB and PB generally increase higher in the stratigraphic section, whereas sulfur in samples from the GRB shows no tendency to evolve heavier isotope ratios. Ratios in GRB samples are much more variable than in samples from the other two basins. This variability is related to the volcanic-ash content; the sedimentary sulfur becomes enriched in ^{32}S where the sediment is enriched in ash. This enrichment relationship suggests that the ash provided an increment of sulfate to Gosiute's lake waters.

The diagenetic environment of all these sediments is reflected in the mineralogy of the sulfides they contain. Highly unusual, bladed sulfides occur throughout cores from all three basins. Pyrrhotite is not typical of sedimentary sulfides; however, petrographic evidence indicates both that the original mineralogy of this bladed sulfide was (and sometimes still is) pyrrhotite and that this mineral formed during a post-early-diagenetic event. Bladed pyrite and marcasite are pseudomorphic after pyrrhotite attesting to changes in the geochemistry of the sediments during late-stage diagenesis.

Our results show that sulfur geochemistry can be used to identify fine-scale changes in lake and sediment geochemistry occurring as these oil shale-rich units were deposited and subsequently modified by diagenetic processes. These geochemical changes can then be related to oil-shale quantity and quality, thus increasing our knowledge of the genesis of these unusual deposits.

POTENTIAL GAS GENERATION IN SUBDUCTED SEDIMENTS OF THE EASTERN ALEUTIAN TRENCH AREA

Roland von Huene

Sediment being subducted in the eastern Aleutian Trench has a potential to generate large volumes of gas, even though the content of organic carbon in the sediment is low, averaging about 0.4 percent. This high potential for gas generation results primarily from the enormous volume of sediment undergoing subduction. Along the eastern Aleutian Arc-Trench system, an average 3-km-thick sheet of sediment is being subducted at the rate of about 60 km per million years. The geothermal gradient in this region is generally 30°C/km, based on one series of measurements in a deep well and on the depth of the base of the gas-hydrate zone. Such a gradient suggests a temperature regime in which the maximum gas generation in the subducting sediment occurs beneath the upper slope. Thus the sediment of the upper slope, as opposed to that of the shelf, could be the most prospective for gas accumulation if suitable migration paths and reservoirs are present.

GEOPRESSURED-GEOTHERMAL ENERGY POTENTIAL—1986

Raymond H. Wallace, Jr.

The concept of a geopressured-geothermal energy resource was introduced in 1966 by U.S. Geological Survey researcher Paul H. Jones. Preliminary characterizations of the resource, estimates of the resource base and predictions of recoverability have been based primarily upon assumed hydrogeologic and production models extrapolated from petroleum industry experience. No commercial wells have yet been drilled and produced to recover the three energy forms offered by this hybrid resource—geothermal energy, natural gas, and mechanical (hydraulic) energy. However, considerable new knowledge of geopressured-geothermal aquifer systems has been gained within the past decade through USGS and other Federally sponsored research, including short-term tests of nine wells-of-opportunity and long-term tests of four research wells. Continuing USGS studies of recoverability are based primarily on results from these tests.

Upper Cretaceous to lower Miocene geopressured aquifers, ranging in depth from 9,745 to 16,750 ft, have been tested. Temperatures of reservoir fluids have ranged from 234° to 327°F and salinities have ranged from 12,800 to 190,900 mg/L. The assumption used in USGS estimates of the resource base, that geopressured aquifers are saturated with methane gas, has been verified; indeed, several of the 13 wells tested produced gas in excess of saturation. Near-wellbore exsolution or presence of a low free-gas phase in the aquifers may explain the saturation. In addition, all the wells on long-term production have unexpectedly produced liquid aromatic hydrocarbon compounds.

Flow-rates ranging as high as 36,500 bbls/day have been achieved from reservoir volumes of more than 0.4 mi^3. However, available reservoir properties data and well test results are inconclusive in establishing long-term sustained production rates. Permeabilities have been found to be higher than predicted by conventional techniques by a factor of 3 to 5. Most importantly, two of the four long-term well tests have revealed a yet-to-be-defined reservoir pressure-sustaining mechanism. Possible mechanisms include stress-dependent compressibility, long-term formation creep, shale-water recharge, cross-flow from adjacent sands, and leakage along boundary faults.

Early production scenarios considered extraction of all three forms of this energy resource, although hydraulic energy was recognized as a minor contributor. In the mid to late 1970's, emphasis was focused on the production of natural gas, because of the oil crisis. Within the past 5 years, production of geothermal energy, along with natural gas, has been emphasized. This year, the U.S. Department of Energy and the Electric Power Research Institute will begin testing an innovative system for recovery of these two resources. The experiment is expected to show that each of these two energy forms is of significant value and can be selectively produced in response to market and other conditions.

Parametric studies by the USGS, based on the preliminary well test results, indicate that more than 5 percent of the resource base may be recoverable, particularly if production is enhanced by shale-water recharge, an early concept advanced by the USGS, and the presence of a low free-gas phase in the reservoirs. Recoverability will be better defined when the results of on-going long-term well tests become available.

GEOCHEMICAL PROCESSES AFFECTING THE ZONATION OF VANADIUM, IRON, AND CHROMIUM, AND IMPLICATIONS FOR VANADIUM-URANIUM ORE FORMATION IN THE COLORADO PLATEAU

Richard B. Wanty, George N. Breit, and Martin B. Goldhaber

Tabular, stratabound vanadium-uranium deposits occur in fluvial sandstones of the Salt Wash Member of the Morrison Formation (Upper Jurassic) in southwestern Colorado. The ore is associated with coalified organic debris and iron sulfides; ore generally conforms to bedding planes but locally crosses them. Laterally displaced from the V-U orebodies by distances of up to 20 meters are, in sequence, zones of chromium-rich illite-smectite, and hematite (iron deposits). The iron deposits occur in red (oxidized) rock, and the orebodies and Cr-clay zones occur in reduced (gray) rock. The morphology of the iron deposits mimics that of the V-U orebodies, and the Cr-clay layers conform completely to bedding features. Understanding the chemical properties of V, Fe, and Cr enables us to characterize the hydrochemical processes that formed these deposits.

Predominant vanadium ore phases include a chlorite enriched in V and Fe, and an oxide of V, Fe, and Al, which may be similar to the mineral montroseite (ideally VOOH). Vanadium in the oxide phase is dominantly trivalent—the most reduced and least mobile form of vanadium observed in natural systems. Iron in the oxide phase is dominantly ferric. The conditions of coprecipitation of oxidized Fe and reduced V are not well understood. Laboratory kinetic studies indicate that vanadyl ion is rapidly reduced by H_2S under conditions of pH and ionic strength that could have formed the deposits. Therefore, precipitation of V may have been initiated by reduction of the more soluble vanadyl (VO^{2+}) ion by limited local accumulations of H_2S in the host rock. Hydrogen sulfide in the system also reacted with dissolved iron to form minor amounts of pyrite and marcasite, implying that the ore-forming solutions were infrequently supersaturated with respect to these minerals.

The ore chlorite phase contains trivalent V and divalent Fe. In the chlorite-forming process, the vanadium was probably reduced by H_2S and incorporated into the lattice with the Fe^{2+}. The absence of ferric iron in the chlorite suggests that the chlorite formed in contact with strongly reducing solutions.

The Cr-rich illite-smectite is associated with coalified detrital organic matter along thin horizontal bedding planes near the contact of oxidized (red) and reduced (gray) sandstones. The chromium was probably concentrated by the reduction of dissolved chromate to Cr^{3+} by reaction with the organics and incorporated into the forming clay lattice.

The iron deposits define the contact of oxidized and reduced rocks and consist of bands of sandstone cemented by vanadiferous hematite. The iron deposits formed simultaneously with the V-U deposits, based on petrographic, chemical, and geometric similarities. Precipitation of the hematite was probably due to oxidation of ferrous iron and subsequent hydrolysis.

The similar geometric and petrographic relationships of the three zones suggest that they formed contemporaneously in the same hydrologic regime. Local accumulations of organic debris and sulfide minerals in the Salt Wash Member caused the development of redox gradients. The iron deposits formed farthest from the organic debris under the most oxidizing conditions. The Cr-containing clays formed in thin layers of organic debris that were mildly reducing. The most reduced conditions favored formation of the V-U deposits because the V and U are least soluble under the most strongly reducing conditions. The proposed local redox gradients, superimposed on the large-scale Salt Wash ground-water chemical evolution during diagenesis, led to the formation of these deposits.

Llamas were used to install portable seismographs in remote areas of Newberry Volcano, Oregon. Forty field technicians, 18 mules and horses, 6 wranglers, 6 llamas, and 8 explosives experts were required to field the high-resolution imaging experiment. Photograph by Pat Berge, September 1984.

DEPOSITIONAL CONTROLS ON THE GEOMETRY OF THE WYODAK-ANDERSON COAL BED, NORTHEASTERN WYOMING

Peter D. Warwick and Ronald W. Stanton

The Wyodak-Anderson coal bed (Paleocene, Tongue River Member, Fort Union Formation) is extensively mined in an area about 75 mi long by 10 mi wide that centers around Gillette, Wyoming, on the eastern flank of the Powder River Basin. A preliminary study of closely spaced drill-hole data (at 500–1,000-ft centers) from a 1,500-mi^2 area in the northern part of the mining region indicates that the Wyodak-Anderson coal bed consists of discontinuous, elliptical coal units, generally split into two benches that are separated by less than 6 ft of siltstone or shale. (However, west of our study area, the coal is split by more than 100 ft of sandstone.) The elliptical coal bodies are commonly less than 3 mi wide, 5 mi long, and 80–120 ft thick; they are separated laterally by narrow (less than 1 mi wide), interconnected no-coal or "want" areas.

The "want" areas in the Wyodak-Anderson coal bed are dominated by stacked, medium- to fine-grained sandstone units (25–50 ft thick) and minor interbedded siltstones and shales. These detrital units form an east-west-oriented belt that is as much as 1 mi wide and can be traced for more than 4 mi. Branching out from this belt are merging, smaller (less than 0.25 mi wide) "want" areas that extend for more than 6 mi both north and south away from the larger east-west-oriented belt. Each "want" area laterally interfingers with a 1,000–1,500-ft-wide zone of split coal. The splits pinch out away from the "want" areas into a zone of thickened coal (500–1,000 ft wide) that can be as much as 200 ft thick. This thickened coal zone then rapidly thins into the central coal body with uniform thicknesses of 80–120 ft. Rider beds are thickest (as much as 100 ft thick) where underlain by "want" areas. Where underlain by thick areas of Wyodak-Anderson coal, the riders thin and pinch out laterally or merge with the Wyodak-Anderson coal. These riders range from 1 to 2 mi long and are less than 1 mi wide.

The shape and lithofacies of the "want" areas indicate that they were probably deposited by large east-west- and smaller north-south-oriented channels of a larger north-south fluvial drainage system whose deposits split the Wyodak-Anderson coal west of our study area. The north-south-oriented channels are subparallel to each other and appear to merge in a pattern similar to those of modern anastomosed fluvial channels. The position of these channels was maintained through time by the adjoining thick Wyodak-Anderson peat that probably accumulated in place in topographically higher areas, as in an ombrotrophic swamp. Mineral-rich zones in the coal adjacent to the "want" areas probably represent numerous flood events. The thickening of the Wyodak-Anderson coal adjacent to the "want" areas probably reflects differential compaction, which was enhanced by the higher mineral content and different, less compactible plant types than in the areas of thick, parting-free peat. Peat accumulation ceased in the main Wyodak-Anderson swamp because of increased detrital influx; but in areas underlain by less compactible sandstones and siltstones, higher topography created a platform on which rider peat accumulated.

URANIUM-BEARING SOLUTION-COLLAPSE BRECCIA PIPES IN NORTHERN ARIZONA

Karen J. Wenrich and George H. Billingsley

Thousands of solution-collapse breccia pipes crop out in the canyons and on the plateaus of northern Arizona. The pipes originated in the Mississippian Redwall Limestone and stoped their way upward through the upper Paleozoic strata, locally extending into the Triassic Moenkopi and Chinle Formations. Collapse began shortly after deposition of the Redwall Limestone, about 300 m.y. ago, with infilling of the Upper Mississippian Surprise Canyon Formation into karst depressions. The dissolution of the Redwall Limestone continued to, or at least reactivated during, the Triassic. The uranium mineralization apparently occurred shortly thereafter: U-Pb isotope data for uraninite samples from the Hack Canyon breccia pipes suggest a main period of mineralization of roughly 200 m.y. ago (K. R. Ludwig, oral commun., 1983). The presence of high-grade uranium ore, associated with potentially economic concentrations of Ag, Pb, Zn, Cu, Co, and Ni in some of these pipes, has stimulated mining activity in northern Arizona despite the depressed uranium market.

More than 900 confirmed and suspected breccia pipes have been mapped on the 1,551 mi^2 (4,018 km^2) Hualapai Indian Reservation. The apparent density of pipes is greatest in areas where: (1) Mississippian rock outcrops occur, (2) the rocks are exposed in three dimensions, making the pipes easy to recognize, and (3) modern spring activity is highest. The springs may follow basement structures that have been active since Mississippian time. In addition, many pipes are associated with river channels of the Surprise Canyon Formation. This unit is rich in iron and organic detritus and contains the highest background uranium content of any formation within the Grand Canyon area. Whether formation of these channels was structurally controlled has not been determined, but pipes mapped on the Marble Plateau show distinct northwest and northeast alignments, similar to the orientation of faults in northern Arizona, suggested by E. Shoemaker in 1974 to be parallel to basement structures. Many mineralized pipes, such as the Hack Canyon pipes, occur in clusters. This suggests that the mineralizing fluids had common hydrologic systems possibly using Redwall Limestone caverns or Surprise Canyon channels as pathways, moving into those pipes connected by the same cave or ancient river channel system.

An extensive suite of elements is anomalously concentrated in the breccia pipes: Ag, As, Ba, Cd, Co, Cr, Cs, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sr, V, Zn, and many rare-earth elements. The principal ore minerals are uraninite, chalcopyrite, chalcocite, tennantite-tetrahedrite, galena, sphalerite, millerite, gersdorffite, siegenite, and molybdenite. Common gangue minerals are marcasite, pyrite, barite, dolomite, calcite, and quartz. Marcasite and pyrite appear to have formed prior to the ore minerals, followed closely by chalcopyrite. The Ni and Co phases also appear to be early: gersdorffite crystals are rimmed by later galena. Tennantite-tetrahedrite formed later than both galena and sphalerite. Uraninite, the latest ore mineral, consistently fills interstices. Vuggy quartz, the least common gangue mineral, postdates all ore. A black, pore-filling pyrobitumen, apparently a late phase, rims pyrite, barite, and quartz.

Primary fluid inclusions in dolomite, quartz, and sphalerite show filling temperatures from 80° to 145°C and high salinities, averaging 15 weight percent NaCl (eq). Secondary inclusions in sphalerite have higher filling temperatures from 105° to 173°C, but similar salinities. Rock-Eval pyrolysis of pyrobitumen by L. Pratt in 1985 suggests temperatures did not exceed 150°C following pyrobitumen emplacement.

Except for the presence of uraninite, the breccia pipes are similar to Mississippi Valley-type (MVT) deposits in mineralogy, fluid-inclusion filling temperatures and salinities, as well as in the presence of associated bitumen. Because MVT deposits do not host uranium minerals, a possible two-stage mineralization history of the pipes is suggested, the first stage by the MVT brine and a second forming the uraninite. Four andesite and dacite cobbles associated with the Chinle Formation near Cameron, Ariz., and believed to come from the Triassic Mogollon Highland to the south, have been dated at 222–196 m.y. by Pierce and others in 1985. This age, similar to the 200-m.y. U-Pb date on the Hack Canyon uraninite, suggests that the volcanic rocks of the Mogollon Highland may have been a source for uranium-rich fluids that moved northward along the Precambrian unconformity or major Paleozoic sandstone aquifers to the low-lying terrane occupied by the breccia pipes. Fluids could have been reduced, permitting uraninite precipitation, wherever they encountered pipes containing the pyrite-rich MVT deposits.

THE USE OF MINERAL ALTERATION PATTERNS AND STABLE ISOTOPE COMPOSITION TO INFER A PALEOHYDROLOGIC REGIME

Gene Whitney, H. Roy Northrop, and Paula L. Hansley

The Westwater Canyon Member of the Upper Jurassic Morrison Formation in the southern part of the San Juan Basin, New Mexico, exhibits mineral and isotopic zonation that can be used to infer the conditions of fluid movement and the subsequent mineral-fluid reactions over a distance of at least 60 km. The Westwater Canyon Member is a relatively homogeneous, hydrologically continuous 100-m-thick sequence of massive fluvial sandstones that is bounded above and below by relatively heterogeneous, hydrologically discontinuous units. It thus has served as a primary conduit for fluids within this stratigraphic interval.

We have defined zonation patterns for three key variables that reflect the nature of the mineral-fluid reactions: the abundance and mineralogy of the interstitial authigenic clay minerals, the stable isotope composition of the clay minerals, and the etching of certain framework grains. Within the Westwater Canyon Member, the proportion of illite layers in diagenetically altered interstratified illite/smectite (I/S) ranges from 0 to 90 percent. The sandstone is most illitic at the center and becomes progressively less illitic toward the upper and lower contacts. Furthermore, the sandstone is most illitic near the center of the basin and becomes less illitic toward the basin margin. The abundance of authigenic chlorite correlates positively with the proportion of illite layers in the I/S, suggesting that the chlorite was precipitated by the same fluid that drove the illitization reaction.

The oxygen and hydrogen isotopic composition of the clay minerals is zoned in a similar manner. The $\delta^{18}O$ and δD values of the clays are a function of the illite content of the I/S, with $\delta^{18}O$ values ranging from +15 per mil (relative to SMOW) for smectite to +12.3 for the most illitic I/S. The δD values range from –116 for smectite to –77 per mil for illitic I/S. The $\delta^{18}O$ value for the chlorite is +7.3 per mil for all points in the study area. The degree of illitization and the isotopic composition of the clays suggest a fluid temperature of around 130°C and fluid $\delta^{18}O$ and δD values of +3 and –50 per mil, respectively. These values are similar to those measured in oil field brines from other midcontinent basins.

The distribution of diagenetically etched detrital garnet is nearly identical to that of I/S and chlorite in the Westwater Canyon Member. The most deeply etched garnets occur where I/S is the most illitic and chlorite is the most abundant. Outside the zone of etched grains, detrital garnets are well rounded with smooth, unetched surfaces. Laboratory experiments have shown that warm (>75°C) organic-acid-bearing solutions can create etch features on garnets that are identical to the distinctive, crystallographically controlled etch faces on Westwater Canyon Member garnets. These results and known concentrations of organic matter in the Westwater Canyon Member suggest that the hydrolysis of organic matter may have produced the soluble organic acids responsible for the etching.

These patterns of mineral-fluid reactions suggest a basinwide paleohydrologic regime in which warm, evolved fluids have migrated updip from the center of the basin under the influence of a regional hydraulic head. The reactions probably resulted from a brief, tectonically induced pulse of fluid. Such a fluid movement event is consistent with the movement of petroleum-related fluids in overlying rocks during the Tertiary in the San Juan Basin.

TECTONICS—A FIRST-ORDER CONTROL OF SEDIMENT DISTRIBUTION AND HYDROCARBON POTENTIAL: EXAMPLES FROM THE WESTERN MARGIN OF NORTH AMERICA

Thomas J. Wiley

Tectonic setting is one of the first-order controls that affect the distribution and hydrocarbon potential of thick sedimentary sequences. Comparative studies of divergent, transform, and convergent margins suggest a positive correlation between tectonic setting and basin morphology, rock types, heat flow, and rates of sedimentation, subsidence, and uplift. Tectonic setting therefore affects both the quality of source and reservoir beds and the timing of hydrocarbon generation, migration, and pooling. The continental margin of Western North America includes divergent tectonics in northern Alaska (production and proven reserves of 11.79 billion bbl of oil and 35.34 TCF of gas) and the Gulf of California; transform tectonics along the San Andreas and Queen Charlotte–Fairweather fault systems (production and proven reserves of 25.63 billion bbl of oil and 25.14 TCF of gas along the San Andreas system); and convergent tectonics in southwestern Alaska (production and proven reserves of 1.15 billion bbl of oil and 7.99 TCF of gas) and northern California to southwestern British Columbia (production and proven reserves of 0.17 TCF of gas). Although hydrocarbon shows have been reported from each margin segment, the major producing basins occur along the San Andreas fault in central and southern California, at Cook Inlet, and on the North Slope. Only Neogene-sourced oil and gas accumulations along the San Andreas fault system developed within a single tectonic setting. Some of California's Great Valley fields, and Alaska's North Slope and Cook Inlet fields, owe their large oil and gas deposits to changes in tectonic setting, to accretion of allochthonous terranes, or to overprinting of different tectonic styles.

Gas-prone Cretaceous and Paleogene source beds in the Great Valley of California originally formed on a convergent margin. The change to a transform setting in the San Joaquin segment resulted in deep burial of the older section by Neogene strata. Transform-related en echelon folding in the Neogene created large structural traps along the valley's western side, and easterly regional dips allowed migration of hydrocarbons from deeply buried source rocks to these traps.

Mesozoic source rocks for Cook Inlet oil and gas fields developed on a convergent margin that was later modified by wrench tectonics. Paleomagnetic data from the Peninsula terrane indicate that Mesozoic (Jurassic) source beds were deposited in lower latitudes and subsequently transported northward and accreted to Alaska. Neogene wrench faulting buried the Mesozoic strata with a thick Tertiary section, and hydrocarbons moved from the older rocks into reservoirs in the younger sequence.

The North Slope of Alaska lies on a divergent margin that formed when the Arctic Ocean (Canada Basin) opened in Late Jurassic to Early Cretaceous time. However, source beds for the oil in the large North Slope fields are probably Cretaceous strata deposited in the Colville foredeep to the south. Presumably a large back-arc basin related to Alaska's Pacific margin, the foredeep was created by isostatic loading of adjacent crust with thrust sheets of the Brooks Range.

The Beringian margin (Bering shelf and slope) remains largely undrilled. Seismic data show a thick sequence of strata underlain by oceanic crust at the base of the slope and en echelon structures in acoustic basement overlain by a thick sedimentary section at the edge of the shelf. The most likely history for this margin segment is thus a combination of transform motion and oblique convergence, a tectonic style that is similar to the hydrocarbon-rich central and southern California transform margin.

ENERGY RESOURCE PROGRAMS

The following abstracts overview and tie together research discussed in detail in preceding pages: they show the interrelation and cooperation among USGS programs and scientific groups, as well as the broad extent of USGS energy research. These abstracts briefly explain the various Energy Resource Programs, dealing with oil and gas, oil shale, coal, geothermal energy, uranium and thorium, and the evolution of sedimentary basins; a detailed explanation of each program is presented in a poster session. The programs have the following goals:

To assess the energy resource potential of specific areas in the United States (particularly Federal lands) for resource management and Congressional action.

To provide timely assessments of the Nation's energy resources. Such information is important for foreign and domestic policy decisions and for long-range planning related to energy supply.

To develop information on the quality of such energy resources as coal and oil shale and other unconventional hydrocarbon resources as a basis for decisions on technology development and resource utilization.

To identify new areas for exploration and develop new concepts of energy deposit formation and distribution to increase our known energy resources.

To improve current methodology and develop new techniques for identifying and evaluating energy resources and analyzing resource data more efficiently and more precisely.

USGS energy resource assessments are used in land-management decisions at all levels of government, from the Congress and the Executive Branch of the Federal Government to State and local governments, and may also provide planning baseline information to industry. Resource and geoscience data generated through the programs provide basic information used for long-range planning for availability of energy resources on a national and international scale.

THE U.S. GEOLOGICAL SURVEY OIL SHALE PROGRAM

Thomas D. Fouch and John R. Dyni

The full responsibility for United States Government geologic studies of oil shale and associated deposits is assigned to the U.S. Geological Survey. The goals of the USGS Oil Shale Investigations Program are:

- To increase our knowledge of the geology and chemistry of oil shales and associated metals and industrial minerals;
- To understand the basic geologic and geochemical processes that form and preserve oil shale in nature and determine its quality;
- To apply this knowledge to the development of regional and national resource assessments;
- To characterize the geology, mineralogy, and chemistry of oil-shale rocks so that the shale-oil resources may be maximally exploited with minimum environmental impact;
- To develop laboratory and field methods for assessing the quantity and quality of oil-shale deposits.

The Oil Shale Investigations Program concentrates much of its effort on research topics and geographic areas in which study results can be expected to affect government and industry activities most significantly. Historic oil-shale investigations have concentrated on field and laboratory studies of the lacustrine Eocene Green River Formation of Utah, Colorado, and Wyoming, focusing on the content and quality of oil shale on or near sites of current or proposed mining activity. The results of these studies are published resource maps of selected shale units and detailed geologic maps of parts of the Piceance and Uinta basins in Utah and Colorado. In addition, published reports include multidisciplinary baseline studies on the chemistry and mineralogy of oil shale and surficial materials. New program objectives place increased emphasis on determining the mineralogy and chemistry of oil-shale units.

Plans for fiscal 1986 underscore compilation of the geologic framework, fracture network, mineralogy, and geochemistry of Green River Formation rocks in the northern part of the Piceance basin and for parts of the Uinta Basin. Although the general extent of the oil-shale resource is known, its development potential is restricted by water-conducting fracture systems, and by chemical and mineralogical variations that result from variations in the lake's depositional character in space and time. Therefore, the program emphasizes geologic and geochemical studies that will determine the amount and distribution of (1) associated sodium-aluminum minerals that are potentially useful by-products of oil-shale processing, (2) minerals which may adversely affect shale-retorting processes, and (3) host minerals that might contain minor and trace elements of environmental concern. Studies of the chemistry and stable isotope composition of mineral species will determine the depositional and diagenetic history of the shales and its relation to chemical and mineral variations. Ongoing mapping and studies of water-conducting fracture systems should allow more effective utilization of oil-shale resources.

Results of these new multidisciplinary studies will be compiled as geologic maps and reports that discuss a wide range of factors relative to effective characterization and utilization of the resources. Other efforts will concentrate on mapping and study of other oil shales and organically enriched rocks in the western part of the United States, and on developing and testing new methods for determining shale-oil yields and shale-oil quality from rocks. Research of the USGS Oil Shale Program has served and will continue to serve the geologic needs of industry, members of the scientific public, and governmental agencies involved in development planning and regulation.

THE U.S. GEOLOGICAL SURVEY EVOLUTION OF SEDIMENTARY BASINS PROGRAM

Thomas D. Fouch, B. H. Kent, J. W. Schmoker, J. L. Ridgley, K. J. Englund, and K. J. Bird

Rocks of sedimentary basins host most of the United States' energy resources, most of its industrial and agricultural minerals, and a large proportion of its metallic-mineral resources. Several U.S. Geological Survey programs, focused on specific energy and metal commodities, presently investigate specialized geologic problems in sedimentary units. Because the collective impact of these studies leaves a large number of basic geologic questions unanswered, the Evolution of Sedimentary Basins Program (ESB) was initiated in October 1984. ESB is a broad-based scientific approach to understanding processes at work in sedimentary basins and rocks. The principal goals of the ESB Program are five-fold:

1. To provide a coordinated and multidisciplinary approach to research studies of the evolution and constituents of sedimentary basins. Studies include sedimentary-rock geology, crustal processes, tectonic evolution, geothermometry, paleohydrology, petrography, geochemistry, sedimentologic and depositional evolution, organic-matter content and thermal history, lithofacies and biological facies, and habitats of mineral and energy resources.
2. To explore the chemical and physical composition, history of movement, and interaction of mineral and sediment grains, biologic constituents, and fluid or gaseous matter through various stages of lithification and alteration during basin burial and uplift.
3. To form an integrated geologic framework using new information from surface-rock exposures, in combination with borehole geophysical, electrical, and lithologic logs, and cored-rock, gravity, magnetic, and seismic-reflection and refraction studies.
4. To develop and distribute new maps, charts, analyses, and other data, and to offer state-of-the-art interpretation of this information.
5. To provide data and interpretations so that resource and hazard evaluations can be developed in a timely manner.

Initial program studies are directed at understanding the physical and chemical evolution of the geologic framework of four geologically diverse basins: (1) the North Slope basin, Alaska; (2) the Anadarko basin, Oklahoma, Texas, and Kansas; (3) the Powder River basin, Wyoming and Montana; and (4) the Central Appalachian basin, West Virginia, Virginia, Tennessee, and Kentucky. Subsequent paleohydrologic and diagenetic studies will rely on and be placed in the context of the established basin framework. Additional ESB-type efforts are underway in the San Juan and Uinta/Piceance basins.

Results of these Evolution of Sedimentary Basins studies serve industry, governmental agencies, colleges and universities and associated scientists, and other members of the technical public whose concerns require insight into the evolution, nature, and geologic character of sedimentary basins and rocks.

THE U.S. GEOLOGICAL SURVEY URANIUM AND THORIUM PROGRAM

Thomas D. Fouch and Jennie L. Ridgley

In 1984, the full responsibility for the geologic resources studies of uranium and thorium deposits was passed from the U.S. Department of Energy (DOE) to the USGS. The transfer of that responsibility has somewhat altered the USGS basic science program of uranium and thorium investigations to reflect the Survey's requirement to respond to the Nation's need for basic information on uranium and thorium geology and resources. As a result, the current goals of the USGS Uranium and Thorium research program are (1) to improve the understanding of the geologic habitat and distribution of identified domestic resources of uranium and thorium, (2) to apply this understanding to the development of regional guides to assess the undiscovered resources, and (3) to develop techniques for increasing the discovery rate and exploitation of economically recoverable nuclear raw materials. Attainment of these goals permits the USGS to advance the basic science of uranium and thorium geology, to provide information on undiscovered uranium and thorium endowment to the Energy Information Administration (EIA) of the DOE, and to assess the validity and utility of data sets and samples collected under the DOE's National Uranium Resource Evaluation (NURE) program.

The Uranium and Thorium program concentrates much of its effort on topics or geographic areas where study results can be expected to affect estimates of undiscovered uranium and thorium endowment most significantly. Four major geographic and topical areas for new emphasis have been identified, and program resources are being focused in these areas. They are (1) surficial uranium deposits (SUDS) throughout the United States, (2) uranium in sedimentary breccia pipes of the southern Colorado Plateaus, (3) uranium in metamorphic rocks of the Piedmont physiographic province of the Eastern United States, and (4) uranium in sedimentary rocks of the northern Great Plains. These and other program geologic research studies that are continuing in sedimentary, igneous, and metamorphic rocks in various parts of the United States will produce topical scientific products in the fields of radiogenic and stable isotopes, paleoground-water movement, water-water and rock-water reactions, geochemical redox systems, and organic geochemical–metal deposit relations.

The SUDS project has been examining uraniferous organic-matter-rich sediments in surficial environments in several Western, Rocky Mountain, and Northeastern States. These uraniferous sediments commonly are developed in mountain terrain underlain by granitic rocks. A Holocene boggy meadow in Washington State is currently being mined for uranium. Other surficial deposits of the Southwest United States and southwestern Great Plains are associated with caliche formation.

In northern Arizona, Paleozoic formations contain breccia pipes filled with blocks of country rock (sandstone, shale, and limestone). Some pipes are mineralized with uranium, copper, cobalt, and precious metals. Mineralized pipes in the region contain small but rich uranium orebodies, some of which are now the focus of mining activity.

In Virginia, altered Paleozoic metamorphic rocks of the Piedmont province are locally rich in uranium minerals. Similar occurrences may exist elsewhere in the province where tectonic and mineralizing events seem comparable.

USGS Uranium and Thorium program efforts, begun before 1984, will continue in the San Juan and other Rocky Mountain basins, in the Lake City caldera region of southwest Colorado, and through topical studies of world-class uranium deposits.

Breaking the silence of an Alaskan midsummer night, a 3,000-lb explosion detonated in the terminus of the Rude River glacier in the Chugach Mountains generates seismic waves being used to decipher crustal structure along the trans-Alaska pipeline corridor. This glacier pond south of Cordova Peak near the Contact fault—suture between Chugach and Prince William terranes—was used both as an intermediate shotpoint on a 120-km seismic refraction profile extending from Copper River delta due north across suture zone and as an off-end shotpoint on a 135-km strike profile within Prince William terrane extending across Hawkins, Hinchinbrook, and Montague Islands. Original color slide by G. S. Fuis, June 1985.

THE U.S. GEOLOGICAL SURVEY COAL RESOURCES PROGRAM

H. J. Gluskoter

The USGS coal program is interdisciplinary in nature, and much cooperative research involving several areas of the USGS is currently underway. These efforts include microcomputer system development, organic geochemistry investigations, isotopic and elemental analyses, and hydrologic, paleontologic, paleoecologic, paleobotanic, and mapping studies. The USGS Coal Resources Program has as its primary purpose the development of a scientific understanding of the origin, distribution, mode of occurrence, character, and extent of the coal resources of the Nation. The coal program consists of three subprograms: (1) Coal Investigation Studies, (2) National Coal Resources Data System (NCRDS) and Information Transfer Studies, and (3) Coal Basin Analysis, a subprogram designed specifically to contribute to the Evolution of Sedimentary Basins Program.

The goals of the Coal Investigation Program are:

— To produce scientifically based assessments of the quality and quantity of United States coal resources.

— To understand the geological and chemical processes and conditions existing during coal formation, and the influence of those processes and conditions on coal quality.

— To determine the basic chemical nature of coal and the distribution of contaminants such as sulfur, ash and other impurities which affect the environmentally acceptable utilization of the coal.

— To develop predictive models for the origin and distribution of the chemical components of coal.

— To develop and maintain a computerized National Coal Resources Data System that provides USGS scientists, other Federal and State scientists, and the public sector ready access to a large collection of information on the Nation's coal resources.

— To provide geotechnical, geochemical, and other basic geologic data to those concerned with coal exploration, coal production, and coal utilization, so that these activities may be carried out in an efficient, safe, and environmentally acceptable manner.

Major accomplishments of the program in fiscal 1985 include (a) transfer of NCRDS from a central computer to a mini-computer system, which will lower operating costs, allow for the addition of a geostatistical program for performing coal deposit assessments, and make the system more accessible to all users; (b) entry of 30,000 records of drill-hole data in NCRDS; (c) completion of coal resources assessments for 30 counties in 7 States (Colorado, Kansas, Missouri, Montana, Pennsylvania, Texas, and Virginia); (d) completion of a summary report for the U.S. Department of Energy on the distribution of certain chemical elements in the coals on record in the U.S. Bureau of Mines Coal Reserve Base; (e) completion of coal-geologic and engineering and hazards studies for ten 1:100,000-scale quadrangles in the West as part of the coal-folio project; (f) realignment of coal basin studies to concentrate about 50 percent of effort on analyses of coal-bearing basins; (g) support for development of a method to remove pyrite from coal by first producing a ferro-magnetic particle (patent applied for); (h) completion of reports on a study of the geologic factors that control variations of mineral matter in the Upper Freeport coal bed, central Pennsylvania; (i) completion of a summary of the coal resources of the National Petroleum Reserve of Alaska; (j) compilation of the coal geology map of North America; (k) assistance with coal geology studies in China, Costa Rica, and the Philippines; and (l) publication of a predictive model of the development of fossil fuels and mineral deposits in rift valleys.

THE U.S. GEOLOGICAL SURVEY GEOTHERMAL RESEARCH PROGRAM

L. J. Patrick Muffler and Manuel Nathenson

The goal of the USGS Geothermal Research Program is to understand the nature, distribution, and magnitude of geothermal resources of the United States, as a basis for determining the proper role of geothermal energy as one alternative energy source in national energy policy. This goal is accomplished through multidisciplinary research designed to (1) determine the geological and hydrological factors that control the characteristics, occurrence, longevity, and size of all types of geothermal systems; (2) estimate the location and magnitude of the Nation's geothermal resources, periodically updating these assessments as new information becomes available and assessment methodologies are refined; and (3) evaluate geoenvironmental effects attendant to extraction and injection of geothermal fluids.

The Geothermal Research Program in the 1970's and early 1980's focused on hydrothermal convection systems, generally at depths less than 3 km. Major accomplishments included (1) three national assessments of geothermal resources; (2) comprehensive multidisciplinary studies of major geothermal regions, including The Geysers, Long Valley, Coso, Yellowstone, Raft River, and the Snake River Plain; (3) development of new methods to interpret water and gas analyses to give subsurface temperatures and to elucidate reservoir processes; (4) development of electrical and electromagnetic techniques to determine the geometry of geothermal systems; (5) development of various passive and active seismic techniques for investigation of hydrothermal systems and underlying intrusive complexes; and (6) development of hydrologic models to describe mathematically the behavior of geothermal systems.

The current trends of the Geothermal Research Program are a decreasing emphasis on the shallower hydrothermal convection systems and increasing emphasis on all types of geothermal energy (including magma and hot dry rock) associated with young igneous systems. The current program has five major components:

— A multiyear, multidisciplinary program to understand the tectonics, geology, and hydrology of the Cascade Range as a framework for characterizing and quantifying the geothermal resources of the range.

— Isotopic and chemical studies to refine geothermometers, elucidate hydrothermal processes, determine the origin of chemical constituents in geothermal fluids, and contribute to the reservoir engineering of geothermal reservoirs under development.

— Increased study of young igneous systems, in particular, development of advanced seismic tomographic techniques to identify and characterize magma bodies.

— Studies of the interaction of magma and geothermal fluids in the roots of hydrothermal systems, focusing on the physical and chemical processes by which energy and mass are transported through the crust in volcanic areas.

— Investigations into selected geoenvironmental concerns of geothermal development, including seismic activity in areas under production and evaluation of the extent to which thermal features in national parks might be affected by geothermal development in adjacent areas.
— Cooperation with the U.S. Department of Energy, the U.S. Agency for International Development, and foreign governments in the evaluation of geothermal energy in Latin America.

U.S. GEOLOGICAL SURVEY ONSHORE OIL AND GAS PROGRAM

Dudley D. Rice

The Onshore Oil and Gas Program consists of basic and applied research focused on both topical and regional problems related to the origin, migration, accumulation, and resource assessment of hydrocarbons. The objectives of the program are to develop and apply concepts and techniques that will improve our ability to better understand mechanisms that lead to generation of hydrocarbons from suitable source beds, as well as identify resource potential, especially in Frontier areas, on Federal lands, and from unconventional sources. Attainment of these objectives requires a multidisciplinary approach, utilizing both field and laboratory studies.

At present, the Onshore Oil and Gas Program is concentrated on (a) hydrocarbon resource assessment of Federal lands of United States and foreign countries; (b) production of maps for the Atlas of Oil and Gas Information; (c) geologic characterization of unconventional hydrocarbon resources, such as coal-bed gas, gas hydrates, Devonian black shales, and tight gas sands; (d) construction of Thermal Maturation Map of the United States; (e) geologic characterization and hydrocarbon resource assessment of the Arctic National Wildlife Refuge (ANWR); (f) seismic studies concerned with mapping of subsurface structures and stratigraphy; (g) the use of Artificial Intelligence (AI) as an aid in identifying depositional environments; (h) geochemical investigations of hydrocarbon-forming processes and their relation to mineral-forming processes; (i) studies of modern and ancient sedimentary sequences, leading to prediction of reservoir- and source-rock distribution and properties; and (j) structural studies focusing on overthrust belts.

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