The Petroleum System—Status of Research and Methods, 1992

U.S. GEOLOGICAL SURVEY BULLETIN 2007

PETROLEUM SYSTEM DEFINITION

A petroleum system encompasses a mature hydrocarbon source-rock and all generated oil and gas accumulations and includes all the geologic elements and processes that are essential if an oil and gas deposit is to exist. **Petroleum** includes high concentrations of any of the following substances: thermal and microbial natural gas found in conventional reservoirs as well as in gas hydrate, tight reservoirs, fractured shale, and coal; and condensates, crude oils, heavy oils, and solid bitumen found in reservoirs, generally in siliciclastic and carbonate rocks. **System** describes the interdependent elements and processes that form the functional unit that creates hydrocarbon accumulations. The elements include a petroleum source rock, reservoir rock, seal rock, and overburden rock whereas the processes are trap formation and the generation, migration, and accumulation of hydrocarbons. These essential elements and processes must be correctly placed in time and space so that organic matter included in a source rock can be converted into a petroleum deposit. A petroleum system exists wherever all these essential elements and processes are known to occur or are thought to have a reasonable chance or probability to occur.

Characteristics and Limits.—The areal, stratigraphic, and temporal extent of the petroleum system is specific, as depicted in figures 1 to 4 for the Deer–Boar(.) petroleum system. The figures are as follows: a **burial history chart** depicts the critical moment (defined below) and the essential elements; a **map** and a **cross section** drawn at the critical moment depicts the spatial relation of the essential elements; and a petroleum system **events chart** shows the temporal relation of the essential elements and processes, and shows the duration time and the preservation time for the system. The duration of a system is the time required to deposit the essential elements and to complete the processes. The critical moment is usually near the end of the duration time when most hydrocarbons are migrating and accumulating in their primary traps. During the preservation time, existing hydrocarbons are either preserved, modified, or destroyed.

The **critical moment** of a petroleum system is based on the burial history chart of the stratigraphic section where the source rock is at maximum burial depth. If properly constructed, the burial history chart shows the time when most of the hydrocarbons are generated. Geologically, migration and accumulation of petroleum occurs over a short time span, or in a geologic moment. Included with burial history curves, the essential elements of this system are shown; for example, in figure 1 the Deer Shale is the source rock.

The areal extent of the petroleum system at the critical moment is defined by a line that circumscribes the mature source rock and all oil and gas deposits, conventional and unconventional, originating from that source at the time of secondary migration. A plan map drawn for the end of Paleozoic time, showing a line that circumscribes the pod of mature source rock and all related hydrocarbon accumulations, best depicts the areal extent of the system (fig. 2).

Stratigraphically, the system includes the following rock units or essential elements: a petroleum source rock, reservoir rock, seal rock, and overburden rock at the critical moment. The function of the first three rock units are obvious; however, the overburden rock is more subtle, because, in addition to providing the overburden necessary to mature the source rock, it also can have considerable impact on the geometry of the underlying migration path and trap. The cross section, drawn for the end of the Paleozoic to show the geometry of the essential elements at the time of hydrocarbon accumulation, best depicts the stratigraphic extent of the system (fig. 3).

The petroleum system events chart (fig. 4) shows two temporal episodes, the duration time and the preservation time. The duration is the time it took to form a petroleum system, and the preservation is the length of time that the hydrocarbons within that system could have been preserved, modified, or destroyed. A petroleum system needs sufficient amount of geologic time to assemble all the essential elements and to carry out the processes needed to form a petroleum deposit. If the source rock is the first element or oldest unit deposited and the overburden rock necessary to mature the source rock is the last or youngest element, then the age difference between the oldest and youngest element is the duration time of the petroleum system.

Preservation time starts after generation, migration, and accumulation processes are complete. Processes that may occur during the preservation time are remigration, physical or biological degradation, or complete destruction of the hydrocarbons. During the preservation time, remigrated (tertiary migration) petroleum can accumulate in reservoirs deposited after the duration time. If insignificant tectonic activity occurs during the preservation time, accumulations remain in their original position. Remigration happens during the preservation time only if folding, faulting, uplift, or erosion occur. If all accumulations and essential elements are destroyed during the preservation time, then the evidence that a petroleum system existed is absent. An incomplete or just completed petroleum system is still in its duration time and thus is without a preservation time.

Level of Certainty.—A petroleum system can be identified at three levels of certainty: known, hypothetical, and speculative. The level of certainty indicates the confidence for which a particular mature pod of source rock has generated the hydrocarbons in an accumulation. In a known petroleum system, in the case of oil, a good geochemical match exists between the source rock and the oil accumulations, or, in the case of natural gas, the gas is produced from a gas source rock. In a hypothetical petroleum system, geochemical information identifies a source rock, but no geochemical match exists between the source rock and the petroleum deposits. In a speculative petroleum system, the existence of source rocks and petroleum accumulations is postulated entirely on the basis of geologic or geophysical evidence. At the end of the system's name, the level of certainty is indicated by (!) for known, (.) for hypothetical, and (?) for speculative.

Petroleum System Name.—The name of the petroleum system includes the source rock, followed by the name of the major reservoir rock, and then the symbol expressing the level of certainty. For example, the Deer–Boar(.) is a hypothetical system consisting of the Deer Shale as the source rock and the Boar Sandstone as the major reservoir rock.

The Petroleum System— Status of Research and Methods, 1992

LESLIE B. MAGOON, Editor

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Leslie B. Magoon, *Editor*

ABSTRACT

This publication, comprising 16 individually authored summaries by U.S. Geological Survey scientists, presents a reorganized table of the petroleum systems within the United States and summarizes the status of research for a number of petroleum-related topics and investigative methods.

The table of petroleum systems within the United States has been reorganized by Magoon to show that a source rock interval can extend beyond a single system to be included in other systems, and to show, as other authors have, that petroleum source rocks occur unevenly throughout geological time. Lewan discusses the role of hydrous pyrolysis as a method to simulate the generation and expulsion of petroleum from a source rock. Clayton focuses on bacteria that mediate coupled oxidation-reduction reactions and use organic and inorganic substrates as a means of obtaining both the carbon and the energy necessary for metabolic processes. Law provides an overview of the occurrence of methane in coal and as an energy source. Normark and Piper examine the turbidite deposit, a potential reservoir rock, using a series of analytical criteria: initiation and flow evolution; transport in channels; flow processes implied from turbidite bedforms; and facies distribution in turbidite systems. Schmoker discusses the growing body of literature dealing with the relation between porosity and time-temperature exposure, or thermal maturity. Schenk covers several petroleum reservoir topics: (1) facies, permeability, and heterogeneity in siliciclastic sandstone reservoirs, (2) various approaches to characterizing fluid-flow heterogeneity in carbonate reservoirs, and (3) mineral transformations in tar sand and heavy oil reservoirs induced by thermal recovery methods. Lillis discusses the use of biological markers as thermal maturity indicators. Naeser highlights the considerable contribution that apatite fission-track analyses have made toward clarifying the thermal history of more than 40 sedimentary basins worldwide. Pawlewicz and King review vitrinite and solid bitumen reflectance and discuss certain thermal maturity correlations and applications. Pollastro reports on the current research status and activities related to clay-mineral geothermometry and, as an example, discusses the use of clay geothermometry as a predictor of oil or microbial gas in the Niobrara Formation. By contouring the thermal maturity of the Muddy Sandstone using vitrinite reflectance, Higley and others show that thermal anomalies relate to differences in burial depth, heat flow, and basin hydrodynamics. Nuccio and Fouch discuss the thermal maturity of the Mesaverde Group in the Uinta basin in northeastern Utah. Taylor discusses the origin and function of the National Energy Research Seismic Library (NERSL). Lastly, Colburn presents a list of publications written by personnel of the USGS Branch of Petroleum Geology and published during 1989 and 1990.

Manuscript approved for publication, September 24, 1991.

Identified Petroleum Systems within the United States—1992

By Leslie B. Magoon[1]

INTRODUCTION

Considerable progress has been made toward explaining the usefulness of the petroleum system as an investigative approach for research and exploration. At the Annual Convention of the American Association of Petroleum Geologists, April 10, 1991, W.G. Dow and L.B. Magoon co-convened a well attended AAPG oral session on "The Petroleum System—From Source to Trap." Ten papers were presented. An introductory paper defined the petroleum system (Magoon and Dow, 1991), and an applications paper (Smith, 1991) showed how Shell Oil Company used the petroleum system for the last 25 years to evaluate offshore tracts and onshore exploration ventures. Four papers covered various aspects of the petroleum system (Curiale, 1991; Demaison and Huizinga, 1991; England, 1991; and Lewan, 1991) and four case studies were presented (Bacoccoli and others, 1991; Bird, 1991; Talukdar, 1991; and Ulmishek, 1991). Other papers presented at this meeting indicate that the petroleum system concept is gaining acceptance (Resnick, 1991; Tinker, 1991). In the May 1991 issue of the AAPG *Explorer* magazine, a popularized article about the petroleum system was published (Shirley, 1991).

The petroleum system definition, which appears on the inside of the front and back cover of this bulletin, has been revised and expanded from the previous bulletin (Magoon, 1989a) to include four figures. The text revision and figures expand on the temporal extent of the system by emphasizing the *burial history chart* (fig. 1) as evidence for the timing of generation, migration, and accumulation of hydrocarbons, and the petroleum system *events chart* (fig. 4) more clearly shows the relationship between the essential elements and processes. Also included are the map (fig. 2) and cross section (fig. 3) to show how the geographic and stratigraphic extent of the system are best depicted. Together, these four figures graphically portray what the revised text describes. Because the petroleum system can be classified more than one way, the classification scheme was deleted.

The list of petroleum systems within the United States (table 1) has been reorganized and revised since the last tabulation in 1989, in which 130 systems were identified (Magoon, 1989b). Table 1 was reorganized by age of source rock to more clearly emphasize two important points. First, a petroleum source rock can have an areal distribution beyond any one system and, in fact, can be part of different systems in other areas. Second, as other authors have noted, petroleum source rock intervals are unevenly distributed in the geologic record (Ulmishek and Klemme, 1990). The oldest age of the source rock is used to classify each system in the table. For example, a source rock whose age extends from Late Devonian through Early Mississippian is classified as Devonian.

The total number of petroleum systems remains the same (Magoon, 1989b; table 2), but three names and two certainty levels were revised (table 2). The Elbert Formation is a reservoir rock rather than a source rock (Kent and others, 1988). The New Albany (.) is an oil system rather than gas, and most of the oil is in Chesterian age reservoirs (Barrows and Cluff, 1984). The level of certainty was changed to speculative for both Pennsylvanian systems [Pennsylvanian coals(?); Pennsylvanian–Late Paleozoic(?)] because of a lack of published information. Quotation marks were placed around "A-1" for the Salina "A-1"–Niagaran(!) system to more clearly separate it from Niagaran. As published information about U.S. petroleum systems becomes available, this list will be revised to incorporate the new information.

SOURCE ROCK INTERVALS BY AREA

In table 1, the region(s) and province(s) for the entire United States are listed to show the general areal distribution for each petroleum system. In many instances, each system covers more than one province, which can include one or more basin (structural or sedimentary), uplift (arch), or mountain range (fold and thrust belt). With few exceptions, each system is associated

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Table 1. Identified petroleum systems within the United States as revised and reorganized by age of source rock (modified from Magoon, 1989b, table 2)

[Level of certainty: (!), known; (.), hypothetical; (?), speculative; for certainty definitions see Magoon, 1988b; lith, lithology; pet, petroleum; res, reservoir; S, sandstone; C, carbonate. Region codes (fig. 5) and references are listed below. CSD/C, Geological province code number (Meyer, 1974)/COSUNA chart stratigraphic column number]

AC,	Atlantic Coast region (Jordan and Smith, 1983);	NE,	New England region (Skehan, 1985);
CCA,	Central California region (Bishop and Davis, 1984a);	NMC,	Northern Mid-Continent region (Bergstrom and Morey, 1985);
CSR,	Central and Southern Rockies region (Kent and others, 1988);	NRW,	Northern Rockies/Williston basin region (Ballard and others, 1983);
GB,	Great Basin region (Hintze, 1985);	NW,	Northwest region (Hull and others, 1988);
GC,	Gulf Coast region (Braunstein and others, 1988);	PBR,	Piedmont/Blue Ridge region (Higgins, 1987);
MBA,	Midwestern basin and arches region (Shaver, 1985);	SAL,	Southern Alaska region (Schaff and Gilbert, 1987b);
MC,	Mid-Continent region (Adler, 1987);	SAP,	Southern Appalachian region (Patchen and others, 1985b);
NAL,	Northern Alaska region (Schaff and Gilbert, 1987a);	SCA,	Southern California region (Bishop and Davis, 1984c);
NAP,	Northern Appalachian region (Patchen and others, 1985a);	SSMC,	Southwest/Southwest Mid-Continent region (Hills and Kottlowski, 1983);
NCA,	Northern California region (Bishop and Davis, 1984b);	TOT,	Texas-Oklahoma Tectonic region (Mankin, 1987);

Petroleum systems [source-reservoir(certainty)]	Source type[1]	Res lith	Pet type	Region code	Province	
					Name	CSD/C
Cenozoic						
Cenozoic(.)	III	S	O/G	GC	Gulf Coast basin	220/2-4,10-11
					Gulf Coast	offshore
Neogene–Salt Lake(?)	I	S	Oil	GB	Great Basin province	625/15,16
Pliocene						
Eel River–Rio Dell(?)	II	S	Gas	NCA	Eel River basin	720/1-2
					Pacific	offshore
Beluga–Sterling(.)	III	S	Gas	SAL	Cook Inlet basin	820/13
Miocene						
Miocene(.)	III	S	Gas	GC	Mid-Gulf Coast basin	210/14,16,17
Miocene(?)	II	S	Oil	CCA	Santa Cruz basin	735/6
					Pacific	offshore
Monterey(?)	II	S	Oil	CCA	Northern Coast Range	725/3
					Pacific	offshore
Monterey–Puente(!)	II	S	Oil	SCA	Los Angeles basin	760/8-11
Monterey–Repetto/Pico(.)	II	S	Oil	SCA	Santa Maria basin	750/3
					Ventura basin	755/4-5
					Pacific	offshore
Monterey–Stevens/Kern River(.)	II	S	Oil	CCA	San Joaquin basin	745/16-21,27-29
Monterey–Tinaquaic(.)	II	S	Oil	CCA	Coastal basin	740
				SCA	Santa Maria basin	750/2
					Pacific	offshore
Soda Lake–Painted Rock(.)	II	S	Oil	SCA	Coastal basin	740
					Santa Maria basin	750/1
Eocene						
Domengine–Cierbo/Briones(?)	II	S	O/G	CCA	Northern Coast Range	725/1
Green River–Wasatch(!)	I	S	Oil	CSR	Uinta basin	575
Kreyenhagen–Gatchell(?)	II	S	Oil	CCA	San Joaquin basin	745/16-21,27-29
Ozette–Hoh(!)	III	S	Oil	NW	Western Columbia basin	710/14
Poul Creek(.)	III	S	Oil	SAL	Gulf of Alaska basin	810/24
Sheep Pass–Garrett Ranch(!)	I	S	Oil	GB	Great Basin	625/9
Stepovak–Bear Lake(.)	III	S	Gas	SAL	Alaska Peninsula	825/12
					Bristol Bay basin	845/10,11
Stillwater–Kulthieth(.)	III	S	Oil	SAL	Gulf of Alaska basin	810/24,26,27
Cretaceous						
Aspen/Bear River Nugget/Madison(?)	II	S	Oil	CSR	Green River basin	535/11
				GB	Uinta uplift	570
Austin Chalk(!)	I	C	O/G	GC	Gulf Coast basin	220/1,4,10
Austin Chalk/Eagleford–Woodbine(?)	I	S	Oil	GC	Mid-Gulf Coast basin	210/14,17
					Gulf Coast basin	220/10
					East Texas basin	230
					East Texas basin	260/5,6
Cretaceous(.)	III	S	G/O	CSR	Green River basin	535/12-14

See footnote at end of table.

Table 1. Identified petroleum systems within the United States as revised and reorganized by age of source rock (modified from Magoon, 1989b, table 2)—Continued

Petroleum systems [source-reservoir(certainty)]	Source type[1]	Res lith	Pet type	Region code	Province	
					Name	CSD/C
			Cretaceous			
Cretaceous(!)	III	S	Gas	MC	Sioux uplift	320/1-3
				NMC	Salina basin	380/8
				NRW	Chadron arch	390
					Williston basin	395
					Sweetgrass arch	500
					Central Montana uplift	510
					Powder River basin	515
					Denver basin	540
Cretaceous(?)	III	S	O/G	CSR	Big Horn basin	520/3,4
Cretaceous(?)	III	S	Oil	CSR	Wind River basin	530/8
Cretaceous(?)	III	S	O/G	CSR	Denver basin	540/21
Cretaceous(?)	III	S	Oil	CSR	Powder River basin	515/6
Cretaceous(?)	III	S	Gas	CSR	Green River basin	535/9,15
Cretaceous(?)	III	S	Gas	CSR	North Park basin	545
Cretaceous–Tertiary(?)	III	S	Gas	CSR	Big Horn basin	520/3,4
Cretacous–Tertiary(!)	III	S	Gas	CSR	Wind River basin	530/8
Dollar Bay(.)	II	C	Oil	GC	South Florida	140/31
					Gulf Coast	offshore
Forbes(.)	III	S	Gas	NCA	Sacramento basin	730/27-29
Greenhorn–Dakota(.)	II	S	Oil	CSR	San Juan basin	580/29
Hornbrook(?)	III	S	Gas	NCA	Klamath Mountains	715/3,5
Hue–Sagavanirktok(!)	II	S	Oil	NAL	Arctic Coastal Plain	890/5-6
Lewis–Picture Cliffs(.)	III	S	Gas	CSR	San Juan basin	580/29
Lower Cretaceous–Paluxy(?)	II	S	O/G	GC	Mid-Gulf Coast basin	210
					Gulf Coast basin	220
					Arkla basin	230
					East Texas basin	260
					Gulf Coast	offshore
Mesaverde(.)	III	S	Gas	CSR	Uinta basin	575/16,17
Mesaverde(.)	III	S	Gas	CSR	Piceance basin	595/18
Mancos–Tocito(.)	II	S	Oil	CSR	San Juan basin	580/29
Mancos–Mesaverde(.)	II	S	Gas	CSR	San Juan basin	580/29
Moreno(?)	II	S	Oil	CCA	Northern Coast Range	725
					San Joaquin basin	745/29,16,17
Mowry–Muddy(!)	II	S	Oil	CSR	Denver basin	540/20
Niobrara(!)	II	C	Gas	CSR	Las Animas arch	450/31
				SSMC	Denver basin	540/21
Niobrara/Carlisle–Frontier(!)	II	C	Oil	CSR	Denver basin	540/20,21
Sligo(?)	III	C	Gas	GC	Mid-Gulf Coast basin	210/14
					Gulf Coast basin	220
					Arkla basin	230/7
					East Texas basin	260/5
Starkey–Winters(.)	III	S	Gas	NCA	Sacramento basin	730/20-26
Sunniland(!)	II	C	Oil	GC	South Florida	140/31
					Gulf Coast	offshore
Torok–Nanushuk(.)	III	S	Oil	NAL	Arctic Coastal Plain	890/1-3
Tuscaloosa(.)	II	S	Gas	GC	Gulf Coast basin	220/3,10,11
			Jurassic			
Cotton Valley(?)	III	S	Gas	GC	Mid-Gulf Coast basin	210
					Gulf Coast basin	220/10
					Arkla basin	230
					East Texas basin	260
Curtis–Entrada/Morrison(?)	II	S	Oil	CSR	Green River basin	535/13
					Piceance basin	595/18
Jurassic–Cretaceous(?)	III	S	Gas	---	Atlantic	offshore
Jurassic/Cretaceous(?)	II	S	Oil	NRW	Sweetgrass arch	500/10,11
					Montana folded belt	505/6-8
					Central Montana uplift	510/12
Smackover(!)	II	C	Oil	GC	Mid-Gulf Coast basin	210
					Gulf Coast basin	220
					Arkla basin	230
					East Texas basin	260
					Gulf Coast	offshore
Todilto–Entrada(.)	II	S	Oil	CSR	San Juan basin	580/29
Tuxedni–Hemlock(.)	III	S	Oil	SAL	Cook Inlet basin	820/13

See footnote at end of table.

Table 1. Identified petroleum systems within the United States as revised and reorganized by age of source rock (modified from Magoon, 1989b, table 2)—Continued

Petroleum systems [source-reservoir(certainty)]	Source type[1]	Res lith	Pet type	Region code	Province Name	Province CSD/C
			Triassic			
Ellesmerian(!)	II	S	Oil	NAL	Arctic Coastal Plain	890/1-8
Favret(?)	II	C	Oil	GB	Great Basin	625/2
Newark(?)	II	S	Oil	NE	New England	100/7-9
				PBR	Piedmont Blue Ridge	150/11
				NAP	N Appalachian basin	N160/25,26
			Permian			
Permian(.)	II	C	Oil	SSMC	Permian basin	430/18-20,23
Permian(.)	II	C	Oil	SSMC	Permian basin	430/20-21
Phosphoria–Weber(!)	II	S	Oil	CSR	Montana folded belt	505
				GB	Central Montana uplift	510
				NRW	Powder River basin	515
					Big Horn basin	520
					Yellowstone	525
					Wind River basin	530
					Green River basin	535
					Uinta uplift	570
					Uinta basin	575
					Snake River basin	615/22
					Wasatch uplift	630/23,27,28
			Pennsylvanian			
Desmoinesian–O sandstone(!)	II	C	Oil	CSR	Denver basin	540/20
Minnelusa(!)	II	S	Oil	CSR	Powder River basin	515
					Denver basin	540/10,20
Pennsylvanian(.)	II	C	Oil	SSMC	Permian basin	430/18-20
Pennsylvanian(.)	II	C	Oil	SSMC	Permian basin	430/20-22
Pennsylvanian cannel coals–sandstone(.)	I	S	Oil	NAP	N Appalachian basin	N160/1,2,7-9
				SAP	S Appalachian basin	S160/11-24
Pennsylvanian coals(?)	III	S	Gas	NAP	N Appalachian basin	N160
				SAP	S Appalachian basin	S160
Pennsylvania–Late Paleozoic(?)	III	S	Gas	MC	Forest City basin	335
				SSMC	Arkoma basin	345/4-5
				TOT	S Oklahoma folded belt	350/6
					Chautauqua platform	355/1,2
					Anadarko basin	360/26-29
					Cherokee basin	365
					Nemaha anticline	370/26
					Sedgwick basin	375/25
					Amarillo arch	440
Paradox–Hermosa(.)	II	C	Oil	CSR	Paradox basin	585/23
Tyler(!)	II	S	Oil	NRW	Williston basin	395/23
			Mississippian			
Chainman–Garrett Ranch(!)	II	S	Oil	GB	Great Basin	625/11
Chainman–Simonson(?)	II	C	Oil	GB	Great Basin	625/8,9,11,12, 17,18,20,21
Chainman–White Rim(?)	II	S	Oil	CSR	Paradox basin	585
				GB	Wasatch uplift	630/29
Chester(?)	III	S	Gas	TOT	Warrior basin	200/17-19
Heath–Tyler(!)	II	S	Oil	NRW	Williston basin	395/14
					Central Montana uplift	510/12
Michigan–Stray(.)	II	S	O/G	MBA	Michigan basin	305/4-6
Mississippian coals–sandstones(.)	III	S	Gas	SAP	S Appalachian basin	S160/25-26
Sunbury–Berea(!)	II	S	O/G	NAP	N Appalachian basin	N160/1,2,7,8,16,20
				SAP	S Appalachian basin	S160/18,21
Sunbury–Murrysville(.)	III	S	Gas	NAP	N Appalachian basin	N160/16-18
			Devonian			
Aneth–Elbert/McCracken(?)	II	S	Oil	CSR	Paradox basin	585/23
Antrim(.)	III	S	Gas	MBA	Michigan basin	305/3-5,15

See footnote at end of table.

Table 1. Identified petroleum systems within the United States as revised and reorganized by age of source rock (modified from Magoon, 1989b, table 2)—Continued

Petroleum systems [source-reservoir(certainty)]	Source type[1]	Res lith	Pet type	Region code	Province	
					Name	CSD/C
Devonian						
Bakken–Madison(!)	II	C	Oil	NRW	Williston basin	395/13-20,23
Chattanooga–Fort Payne(.)	III	C	O/G	SAP	S Appalachian basin	S160/11,12
Devonian–Berea(?)	II	S	Oil	MBA	Michigan basin	305/3-5
Devonian Black Shales–Venango(!)	II	S	G/O	NAP	N Appalachian basin	N160/1-29
Devonian–Detroit River/Traverse(?)	II	C	Oil	MBA	Michigan basin	305/4-6
Exshaw–Madison(.)	II	C	Oil	NRW	Sweetgrass arch	500/7,10,11
					Montana folded belt	505
Marcellus–Bass Islands(.)	III	C	Gas	NAP	N Appalachian basin	N160/21,27
Marcellus–Onondaga(.)	III	C	Gas	NAP	N Appalachian basin	N160/21,22,28
Marcellus–Oriskany(.)	III	S	Gas	NAP	N Appalachian basin	N160
Monroe(?)	III	C	Gas	GC	Arkla basin	230/9
New Albany–Chester(.)	II	S	Oil	MBA	Illinois basin	315/7-12,19-21
Ohio–Big Injun(.)	II	S	G/O	NAP	N Appalachian basin	N160/1-3,7-9,16,17
Ohio/Chattanooga–Corniferous(?)	III	C	O/G	SAP	S Appalachian basin	S160/18
				MBA	Cincinnati arch	300/24,25
Ohio Shale(!)	II	S	G/O	NAP	N Appalachian basin	N160
				SAP	S Appalachian basin	S160
Ohio/Sunbury–Greenbriar/Newman(?)	III	C	Gas	NAP	N Appalachian basin	N160/1,2
				SAP	S Appalachian basin	S160/18,21
Ohio–Weir(?)	II	S	Gas	NAP	N Appalachian basin	N160/1-3,7-14
				SAP	S Appalachian basin	S160/18-24
Woodford/Chattanooga–Paleozoic(.)	II	S	Oil	MC	Forest City basin	335
				SSMC	Arkoma basin	345/3-5
				TOT	S Oklahoma folded belt	350/6
					Chautauqua platform	355
					Anadarko basin	360
					Cherokee basin	365
					Nemaha anticline	370/26
					Sedgwick basin	375
					Central Kansas uplift	385
					Chadron arch	390/15
					Amarillo arch	440
					Las Animas arch	450
Woodford–Silurian/Devonian(.)	II	S	Oil	SSMC	Permian basin	430/18-21
Woodford–Sycamore(!)	II	C	Oil	TOT	S Oklahoma folded belt	350/6
Silurian						
Cabot Head–Medina(.)	I	S	Oil	NAP	N Appalachian basin	N160/21
Rose Hill–Keefer(?)	I	S	Gas	NAP	N Appalachian basin	N160
				SAP	S Appalachian basin	S160/18
Salina "A-1"–Niagaran(!)	II	C	Oil	MBA	Michigan basin	305/3-6,15
Salina–Newburg(?)	I	C	Oil	NAP	N Appalachian basin	N160/7,8,15,16,20
Ordovician						
Athens–Trenton/Knox(?)	I	C	Oil	NAP	N Appalachian basin	N160/1-5
				SAP	S Appalachian basin	S160/11-15,17-26
Glenwood–Rose Run(?)	I	S	Oil	NAP	N Appalachian basin	N160/1,2,7,9,16,17,20,21
				SAP	S Appalachian basin	S160/16-18
Glenwood–Trempealeau(?)	I	C	Gas	NAP	N Appalachian basin	N160/15
Ordovician–Prairie du Chien /Black River/Trenton(?)	II	C	Oil	MBA	Cincinnati arch	300/14-17
					Michigan basin	305/2-6,15
Point Pleasant–Clinton(!)	II	S	Oil	NAP	N Appalachian basin	N160/15-16
Simpson–Ellenberger/Simpson(.)	II	C	G/O	SSMC	Permian basin	430/19-21
Simpson–Viola(!)	I	C	Oil	MC	Forest City basin	335
				SSMC	S Oklahoma folded belt	350/6
				TOT	Chautauqua platform	355/1,2
					Anadarko basin	360/27
					Cherokee basin	365
					Nemaha anticline	370/26
					Sedgwick basin	375/25
Simpson–Viola/Hunton(.)	I	C	Oil	MC	Forest City basin	335/21
					Nemaha anticline	370/10,18,20
Trenton(!)	I	C	Oil	MBA	Cincinnati arch	300/13,14
					Illinois basin	315/7-12,19-21
Utica–Beekmantown(!)	II	S	Gas	NE	New England	100/6
					Adirondack uplift	110/1

See footnote at end of table.

Table 1. Identified petroleum systems within the United States as revised and reorganized by age of source rock (modified from Magoon, 1989b, table 2)—Continued

Petroleum systems [source-reservoir(certainty)]	Source type[1]	Res lith	Pet type	Region code	Province	
					Name	CSD/C
			Ordovician			
Utica–Trenton(!)	I	C	Gas	MBA	New England	100/2,3
				NAP	Adirondack uplift	110/1
				NE	N Appalachian basin	N160
					Cincinnati arch	300/13,14,16-18
Viola(!)	II	C	Oil	TOT	S Oklahoma folded belt	350/6
Winnipeg–Red River(!)	II	C	Oil	NRW	Williston basin	395/13-20,23
			Cambrian			
Conasauga–Knox(?)	II	C	Gas	PBR	Piedmont Blue Ridge	150/3-6
				SAP	S Appalachian basin	S160/25,26
Conasauga–Knox(?)	II	C	Oil	SAP	S Appalachian basin	S160/1-8
				TOT	Warrior basin	200/17,18
Conasauga–Rome(.)	II	S	Oil	NAP	N Appalachian basin	N160/1-4,7-14,17,18
				SAP	S Appalachian basin	S160/11-24
EauClair–Knox(?)	II	C	Gas	MBA	Illinois basin	315/8-12,19-21
			Precambrian			
Nonesuch–Keweenawan(?)	II	S	Gas	MC	Wisconsin arch	310/20
				NMC	Sioux uplift	320/12,13
					Iowa shelf	325/3,4,12,14
					Nemaha anticline	370/10,20
					Salina basin	380/17
			Unknown			
Unknown–Eocene(?)	II	S	Oil	GC	Mid-Gulf Coast basin	210
					Gulf Coast basin	220/10
					Arkla basin	230/8
					East Texas basin	260/5
Unknown–Eutaw/Selma(?)	II	S	Oil	GC	Mid-Gulf Coast basin	210/13,14,16,28
					Gulf Coast basin	220/10
					Arkla basin	230
					East Texas basin	260/6
Unknown–San Miguel/Olmos(?)	II	S	Oil	GC	Gulf Coast basin	220/1
				SSMC	Ouachita tectonic belt	400/16

[1]Refers to organic matter type, either I, II, or III, and is distinguished on the basis of the hydrogen and oxygen indices of the kerogen when plotted on the van Krevelen diagram. See Tissot and Welte (1984) for further explanation.

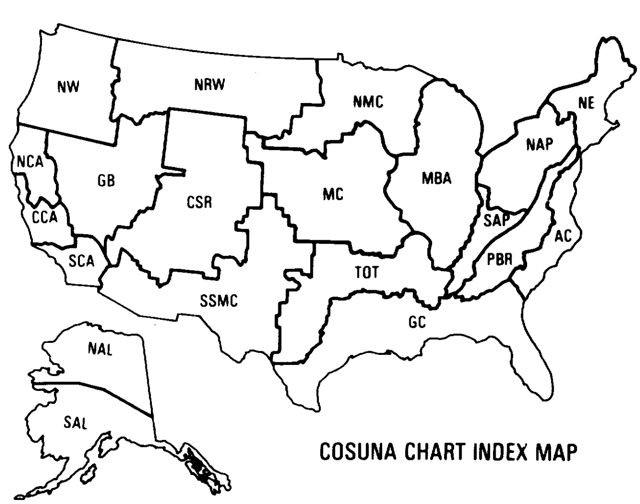

Figure 5. Index map of regions for the *Correlation of stratigraphic units of North America* (COSUNA) charts. See table 1 for region names and references.

Table 2. Name and level of certainty revisions of U.S. petroleum systems

[See text for sources of information leading to these revisions]

Magoon, 1989b	This publication
Aneth/Elbert–McCracken(?)	Aneth–Elbert/McCracken(?)
New Albany(.)	New Albany–Chester(.)
Pennsylvanian coals(!)	Pennsylvanian coals(?)
Pennsylvania–Late Paleozoic(!)	Pennsylvania–Late Paleozoic(?)
Salina A-1–Niagaran(!)	Salina "A-1"–Niagaran(!)

with at least one basin because the basin contains the overburden rock that provided the burial depth (heat) to mature the source rock. Only systems that contain microbial gas have little need for overburden rocks.

When the sedimentary basin of a source rock is on a continental scale, such as the Late Devonian of the United States, that organic-rich interval can be the source rock for more than one petroleum system. However, the stratigraphic nomenclature for this Upper Devonian source rock is different depending on the location (in parenthesis): the Ohio Shale and Devonian black shale (Appalachian area), the Antrim Shale (Michigan basin), the New Albany Shale (Illinois basin), the Woodford Shale (mid-Continent provinces), the Aneth Formation (Paradox basin; Kent and others, 1988), the Pilot Shale (Great Basin), the Bakken Formation (Williston basin), and the Exshaw Formation (Sweetgrass arch). Wherever this organic-rich rock is, or is thought to be, buried enough by overburden rock to generate oil or gas, a petroleum system exists. The petroleum systems that include these Upper Devonian source rocks are listed in table 1 under Devonian.

What matures this Upper Devonian organic-rich interval is overburden rock deposited in smaller, post-Devonian basins (successor basins) located on or along the edge of the North American craton. Sedimentary basins on the craton are sags or rifts, whereas basins at the edge of the craton are foreland basins. Unless the sediments are created in situ (carbonates, evaporites, and coals), the provenance for the sediments dumped into all three basins is the craton, or the provenance for the foreland basin, both craton and the fold and thrust belt. The reservoir and seal rocks are either in the Upper Devonian strata or are part of the overburden rock. The trap- and petroleum-forming processes occur during deposition of the overburden rock.

On a continental scale, the duration of these petroleum systems with Upper Devonian source rocks varies with the location of the system. Along the eastern and southern edge of the North American craton, these late Paleozoic foreland basins include the Appalachian, Warrior, and Anadarko and received only a minor amount of post-Paleozoic sediments. Since the present-day petroleum accumulations had to have been generated and migrated by the end of Permian time or earlier, when maximum burial was achieved, the duration of these petroleum systems with Upper Devonian source rocks ranged from Late Devonian through Permian time. The preservation time extended through the Mesozoic and Cenozoic. In contrast, the western edge of the craton includes foreland basin sedimentary rocks as young as Cretaceous or early Tertiary, and one of the cratonic interior basin sags may be as young as Tertiary. The duration of these systems can range from Late Devonian through Cretaceous or Tertiary, respectively.

Another organic-rich interval that is involved in many petroleum systems is the Miocene of California (table 1). Here, numerous strike-slip basins formed in the Miocene and continue to develop to the present day. At first, the basins were conducive to the formation and preservation of organic matter along with abundant biogenous silica and relatively little siliciclastic material. Deposition of coarser siliciclastic material became progressively more rapid during Pliocene to Pleistocene time; this sediment provided the necessary overburden to generate hydrocarbons in petroleum systems within the Los Angeles basin, Ventura basin (Santa Barbara offshore), Santa Maria basin, San Joaquin basin, and several other coastal basins. Again, what started out as organic-rich deposits over a large area eventually developed into smaller sedimentary basins that acquired sufficient overburden rock to generate hydrocarbons, and thus form separate petroleum systems.

SOURCE ROCK INTERVALS BY TIME

Meissner and others (1984) used a map of the interior part of the United States to show the distribution of hydrocarbon source rocks over nine time intervals. These intervals are as follows: Middle Ordovician, latest Silurian to Late Devonian, Late Devonian to mid-Mississippian, Late Mississippian, Pennsylvanian, Permian to Triassic, Jurassic, Cretaceous, and latest Cretaceous to

Table 3. Distribution of petroleum systems by age and hydrocarbon type

[Age of petroleum system is based on the oldest age of the source rock. Information on age of source rock is from table 1]

Age	No.	Oil	Oil/Gas	Gas/Oil	Gas
Cenozoic undif.	2	1	1	0	0
Pleistocene	0	NA	NA	NA	NA
Pliocene	2	0	0	0	2
Miocene	8	7	0	0	1
Oligocene	0	NA	NA	NA	NA
Eocene	8	6	1	0	1
Paleocene	0	NA	NA	NA	NA
Cretaceous	33	13	4	1	15
Jurassic	7	5	0	0	2
Triassic	3	3	0	0	0
Permian	3	3	0	0	0
Pennsylvanian	9	7	0	0	2
Mississippian	9	4	2	0	3
Devonian	21	9	2	3	7
Silurian	4	3	0	0	1
Ordovician	13	9	0	1	3
Cambrian	4	2	0	0	2
Precambrian	1	0	0	0	1
Unknown	3	3	0	0	0
Total	130	75	10	5	40

early Tertiary. Dividing the geological time scale into 13 segments, Ulmishek and Klemme (1990) inventoried the important source rock intervals in the world and found that six intervals account for 90 percent of the known oil and gas reserves. These six stratigraphic intervals are as follows: Silurian, Late Devonian to Tournaisian (Mississippian), Pennsylvanian to Early Permian, Late Jurassic, mid-Cretaceous, and Oligocene to Miocene.

The distribution of U.S. petroleum systems by age shown in table 1 are summarized by age and hydrocarbon type in table 3. The most common age of the source rock is Cretaceous, whereas the Oligocene and Pleistocene contain none (table 3). The most to least common source-rock ages are as follows: Cretaceous (33), Devonian (21), Ordovician (13), Mississippian (9), Pennsylvanian (9), Eocene (8), Miocene (8), and Jurassic (7). The remainder of the age brackets have fewer than five. For the 130 petroleum systems, 85 were oil or mostly oil and 45 were gas or mostly gas; a ratio of 2:1. Evidently, oil from Ordovician (13) and Eocene (8) source rocks in the United States are unimportant on a worldwide scale (Ulmishek and Klemme, 1990).

SUMMARY

A petroleum system includes all the hydrocarbons that originated either from a pod of mature source rock or, in the case of microbial gas, from an immature source rock. More simply, sedimentary organic matter must be heated over time or acted upon by microbes to generate petroleum. Sedimentary rock matter dumped into basins is the framework into which this organic matter and the resultant petroleum products move and reside. As discussed above, the areal distribution of organic matter for any particular geologic age can range from local to continental, and these rock intervals are unevenly distributed over geologic time. On a worldwide scale only six source-rock intervals generated over 90 percent of known oil and gas (Ulmishek and Klemme, 1990). The amount, type, and thermal maturity of this organic matter must have determined the amount and type of petroleum generated.

The observation that laterally continuous source rocks are commonly involved in more than one petroleum system is important, because then regional studies of organic-rich rocks between systems can be used to better predict the amount and type of organic matter within a system where it is presently overmature. An organic-rich rock between systems is immature and is frequently penetrated by exploratory wells or is exposed at the surface where it can be examined, sampled, and analyzed. In contrast, the same organic-rich rock within a system is mature to overmature at maximum burial depth, is commonly too deeply buried to be sampled, and when analyzed can give a geochemical profile of a depleted source rock.

By examining a source rock at different levels of maturity between and within petroleum systems, and comparing these results with the amount and type of recoverable hydrocarbons (cumulative production plus known reserves), then the efficiency of different petroleum systems can be compared to better assess the ultimate hydrocarbon potential of a system. For example, a map showing the richness, type, and thermal maturity of Upper Devonian organic-rich rocks for North American is necessary if reasonable calculations to determine the amount of hydrocarbons generated are to be compared to recoverable hydrocarbons by the petroleum system method. Properly done, this exercise may provide a reasonable estimate of total amount of ultimately recoverable hydrocarbons by system.

The uneven distribution of source rocks over geologic time indicates that only certain intervals need to be mapped over large areas. Certainly in the United States, strata in the Late Devonian, Cretaceous, and possibly the Ordovician intervals need to be addressed on a continental scale. Tertiary source rocks need to be addressed on a much smaller scale, such as the Miocene of California.

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A Concise Historical and Current Perspective on the Kinetics of Natural Oil Generation

By Michael D. Lewan[1]

Kinetics is the branch of chemistry that studies the time dependency of reactions and the factors controlling reaction rates. The importance of time as well as temperature in oil-shale retorting (Franks and Goodier, 1922; Maier and Zimmerley, 1924) and natural coalification (Huck and Karweil, 1955; Karweil, 1955) was established long before it was recognized as being important in oil generation. Habicht (1964) showed the importance of oil-generation kinetics in identifying effective source rocks in the Gifhorn trough. His approach was theoretically based on the Arrhenius kinetic parameters and first-order reaction rate suggested by Abelson (1964). Subsequently, Philippi (1965) showed the importance of time in assessing the amount of oil generated in the Ventura and Los Angeles basins. His approach was empirically based on organic geochemical data from subsurface wells. Although neither of these studies established an explicit method for evaluating oil-generation kinetics, they demonstrated the importance of time as well as temperature in natural oil generation.

Tissot (1969) presented an explicit kinetic model for oil generation, which was later enhanced by Tissot and Espitalié (1975). This approach assumed an overall reaction of partial decomposition of kerogen to oil by means of six parallel, first-order reactions. Changes in the rate of each of these reactions with temperature were described by the Arrhenius equation, in which each of the six reactions had its own activation energy and frequency factor. In addition to presenting six sets of kinetic parameters for type II kerogens, Tissot and Espitalié (1975) also presented six sets of kinetic parameters for type I and type III kerogens. Each of the six parallel reactions has an assigned activation energy that is the same for all three major kerogen types, but the frequency factor and amount of kerogen consumed for each of the six parallel reactions vary among the three major kerogen types. This discrete distribution of activation energies assumes that only six types of bonds with known bond strengths are cleaved during oil generation. Tissot and Welte (1978, p. 504-505) stated that these prescribed kinetic parameters are based on extractable bitumen from naturally and experimentally matured source rocks, but the rationale and methods by which these values were determined were not presented. Although the derivation of kinetic parameters in this approach is not explicit, it revealed the possibility that one time-temperature relationship may not be sufficient to describe oil generation from all three major kerogen types.

During this same time period, another approach based on coalification was being developed. A kinetic model for changes in reflectivity of vitrinite macerals with increasing coal rank was presented by Lopatin (1971) and later modified by Lopatin and Bostick (1973). This model was calibrated with naturally matured coals and was based on the premise that the reaction rate doubled for every 10°C increase in temperature. The time-temperature indices derived from this approach were then deductively related to stages of oil generation by Hood and others (1975) and Lopatin (1976). The reasonable predictions the Lopatin approach gave for vitrinite reflectances without computer support made it particularly popular in petroleum exploration applications (Waples, 1980). However, its inherent premise that bond cleavage (thermal cracking) in oil generation from all types of kerogen is the same as bond formation (aromatic condensation) in vitrinite maturation was clearly an oversimplification. Although this approach may be considered a good measure of thermal stress experienced within a subsiding sedimentary basin, it is not necessarily a good measure of oil generation.

Although an unspecified amount of experimental pyrolysis data were included in the kinetic model by Tissot and Espitalié (1975), both Arrhenius and Lopatin models were primarily dependent up to this time on available subsurface well data. Uncertainties in these natural data concerning paleotemperatures and gradients, uplift and erosion events, and rock unit ages encouraged the use of laboratory pyrolysis in developing kinetic models. In the years following 1975, the emphasis on laboratory pyrolysis in organic geochemical research increased significantly as recorded by the sharp increase in number of publications on the subject (Barker and Wang, 1988).

[1] U.S. Geological Survey, Denver, Colo.

Three categories under which these laboratory pyrolysis experiments may be grouped include open anhydrous pyrolysis, closed anhydrous pyrolysis, and hydrous pyrolysis. Open anhydrous pyrolysis involves removing vaporized products from the pyrolysis chamber in which they are generated in the absence of liquid water. The product is removed by either a carrier gas that sweeps the vapor products into an external detector (Barker, 1974; Claypool and Reed, 1976) or an external cold trap that condenses liquids from self-purging vapor products (Heistand, 1976; Wildeman, 1977). Closed anhydrous pyrolysis maintains pyrolysis products in the pyrolysis chamber with no liquid water being present. Obtaining a liquid product by this method usually requires extracting the sample with an organic solvent after the experiment has been completed (Harwood, 1977). Hydrous pyrolysis involves pyrolyzing a sample in the presence of liquid water in a closed reactor. If the proper time and temperature conditions are applied to a potential source rock, this method generates an expelled oil that accumulates on the water surface (Lewan and others, 1979; Winters and others, 1983).

In the late 1970's and early 1980's, the proliferation in pyrolysis studies was primarily focused on understanding the processes involved in petroleum formation and on evaluating hydrocarbon potential of source rocks. It was not until the mid-1980's that emphasis was placed on laboratory pyrolysis in the derivation of kinetic models for oil generation. The two major pyrolysis approaches employed during this time were non-isothermal experiments with open anhydrous pyrolysis (Ungerer, 1984; Braum and Burnham, 1987) and isothermal experiments with hydrous pyrolysis (Lewan, 1985).

The non-isothermal approach using open anhydrous pyrolysis for natural oil-generation kinetics was first presented by Ungerer (1984) and later enhanced by Ungerer and others (1986). In the latest version of this approach (Ungerer and Pelet, 1987), aliquots of isolated kerogen are subjected to Rock-Eval pyrolysis at three different heating rates (for example, 0.34, 4.5, and 56°C/min) that span at least two orders of magnitude. The flame-ionization responses to the volatile hydrocarbons generated at the three different heating rates are modeled by assuming that as many as 20 parallel first-order reactions are responsible for the resulting yield curves. These hypothetical reactions are assigned regularly spaced activation energies at 2 kcal/mol intervals between 40 and 80 kcal/mol. A nonlinear optimization computer program (OPTIM) calculates a frequency factor and amount of kerogen consumed for each activation-energy interval that best reproduces the hydrocarbon-generation curves for all three heating rates. Results of this approach presented by Tissot and others (1987) showed narrow activation-energy distributions for oil-prone kerogens, with over 70 percent of hydrocarbon generation from type II kerogens being described by only two parallel reactions within 4 kcal/mol of one another and over 85 percent of hydrocarbon generation from type I kerogen being described by a single parallel reaction within a 2 kcal/mol interval. This kinetic approach has been shown to model changes in hydrocarbon yields as determined by Rock-Eval pyrolysis in the Mahakam Delta (Ungerer and Pelet, 1987), but the relationship between total hydrocarbon yields from Rock-Eval pyrolysis and generation of expelled oil in nature needs further clarification.

Braum and Burnham (1987) discussed the importance of using a distribution of activation energies in describing hydrocarbon generation from non-isothermal experiments. In addition to the discrete distribution employed by Ungerer and others (1986), they also considered the use of a Gaussian distribution in their discussion. This latter approach assumes that hydrocarbon generation consists of a number of first-order parallel reactions, which have the same frequency factor but different activation energies that collectively have a Gaussian distribution. Burnham and others (1987) compared these curve-fitting approaches with data generated by Rock-Eval pyrolysis. The discrete distribution fits the experimental data better than the Gaussian distribution, and when extrapolated to geological conditions, the Gaussian distribution predicts major hydrocarbon generation 10°C to 15°C lower than the discrete distribution. Burnham (1991) also did a similar comparison of curve-fitting approaches with a modified Fischer assay apparatus. This type of open anhydrous pyrolysis generates a condensable oil, which may be kinetically described through a series of isothermal experiments. Unfortunately, the amount of oil generated is inversely dependent of heating rate, which when extrapolated to geological heating rates results in the total absence of a generated oil. In addition to questioning the validity of employing open anhydrous pyrolysis in determining kinetics for natural oil generation, extrapolating the curve-fitting kinetic models from non-isothermal experiments to geological conditions has also been questioned (Lakshmanan and others, 1991).

The approach using isothermal hydrous-pyrolysis experiments for natural oil-generation kinetics was first presented by Lewan (1985). Aliquots of a rock sample are subjected to hydrous pyrolysis at temperatures typically in the range of 300°C to 365°C for 72-hour durations. A first-order rate constant is determined from the amount of expelled oil generated at each temperature and plotted on Arrhenius coordinates (natural log of rate constant versus reciprocal of absolute temperature). The resulting plots are adequately described by a straight line, which provides an activation energy and frequency factor in the classical kinetic approach (Lewan, 1985; Lewan and Buchardt, 1989). Extrapolation of these kinetic parameters to lower temperatures and longer durations gives reliable predictions of oil generation from source rocks subsiding in sedimentary basins (Hunt and others, 1991). Two important concepts that emerged from this experimental approach were that (1) rates of oil generation may vary significantly for type II kerogens and (2) rates of oil generation from type II kerogens increase in part with their organic sulfur content. The former concept further accentuated the limitations of the Lopatin approach as discussed by Wood (1988), and the latter concept was also deduced from natural data by Orr (1985).

Unlike kinetics based on total hydrocarbon evolution from kerogen decomposition by Rock-Eval pyrolysis, hydrous pyrolysis more closely simulates nature and determines the kinetics of oil generation from the partial decomposition of bitumen (Lewan, in press a). As noted by Burnham and others (1987), the inability of Rock-Eval pyrolysis to distinguish between bitumen, oil, and gas results in a broader oil window than that derived from hydrous pyrolysis kinetics. Another consideration is the importance of rapid vaporization of pyrolysis products in obtaining a volatile product from open anhydrous pyrolysis. Lewan (in press b) noted that this process is not operative in subsiding sedimentary basins, but formation of an immiscible oil as observed under hydrous pyrolysis is operative in subsiding sedimentary basins. The importance of water in the natural generation and expulsion of oil is continually becoming more evident, and further research on the kinetics of oil generation by hydrous pyrolysis is needed. As stated by Gardiner (1969), "If you should find that chemical kinetics is an underdeveloped science compared with other aspects of chemistry, be tolerant and recognize that time-dependent problems are intrinsically more difficult than equilibrium ones, or be challenged and spend some of your scientific lifetime improving the situation."

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Role of Microbial Processes in Petroleum Systems

By Jerry L. Clayton[1]

Microorganisms are ubiquitous in most natural aquatic systems and pore waters of shallowly buried sediments (burial depths equivalent to temperatures less than about 100°C). It is widely recognized that microorganisms play major roles in global chemical cycles (for example, carbon, sulfur, iron, nitrogen, and manganese) (Blackburn, 1983; Jørgensen, 1983; Krumbein and Swart, 1983; Nealson, 1983; Burdige and Nealson, 1986; Aller and Rude, 1988; Lovley and Phillips, 1988; Lovley and others, 1987, 1989a,b, 1990). This report reviews the roles of bacteria in the following processes that are important components of petroleum systems: (1) sediment diagenesis, (2) degradation of crude oil, and (3) formation of crude oil and natural gas.

The focus of this paper is on bacteria that mediate coupled oxidation-reduction reactions using both organic and inorganic substrates as a means of obtaining both carbon and the energy necessary for metabolic processes. These types of bacteria obtain carbon from pre-existing organic matter (heterotrophy) or CO_2 (autotrophy) and use either organic or inorganic reactions as a source of energy. Some bacteria obtain carbon from dissolved CO_2 and energy from photosynthesis via anaerobic pathways. Because of the light requirement imposed by photosynthesis, such bacteria are restricted to the phototrophic zone of the water column or to the uppermost sediment layers where the water is shallow enough to allow nearly unimpeded light penetration. Green and purple sulfur bacteria (Chlorobiaceae and Chromatiaceae) are important groups of anaerobic photosynthetic bacteria. Aerobic photosynthesis is carried out by blue-green bacteria living in the upper, phototrophic water column and on the surface of bottom sediments.

Classical methods of classifying bacteria are based on morphology, gram stain reaction, cultural characteristics (that is, the kind of growth on media of different compositions), and biochemical reactions such as sugar fermentations and amino acid and vitamin requirements. More recent classification methods are based on the composition of nucleic acids (Fox and others, 1980). For understanding bacterial effects in petroleum systems, a classification based on energy and carbon source is convenient, because this type of classification groups the organisms according to inorganic products released into the sediment. These inorganic products are important in the formation or degradation of petroleum in that they play a role in mineral diagenesis or affect the carbon budget of the system. Accordingly, bacteria can be classified into two major groups of importance in petroleum systems (table 4). The two groups listed in table 4 include both aerobic and anaerobic types. Autotrophic bacteria use CO_2 as a source of carbon for synthesis of biomolecules and obtain the energy necessary for synthesis from light (photosynthesis) or from oxidation of inorganic substrates (chemosynthesis). These bacterial process are important in organic matter and sediment diagenesis. Heterotrophic bacteria generally use pre-existing organic compounds and are particularly important in degradation of petroleum.

In sediments, bacterial activity generally decreases with increasing depth of burial owing to depletion of nutrients, changing pH or oxidation-reduction potential, accumulation of toxic by-products of metabolism, or increasing temperature. Within this overall trend of decreasing activity, zonation occurs in which different types of bacteria inhabit successive sediment layers in response to changing environmental conditions (Ponnamperuma, 1972; Claypool and Kaplan, 1974; Yoshida, 1975; Champ and others, 1979; Froelich and others, 1979; Winfrey and others, 1981; Reeburgh, 1983). This succession of bacterial populations can be divided into three zones: (1) the aerobic zone; (2) the anaerobic sulfate-reducing zone; and (3) the methanogenesis zone (Claypool and Kaplan, 1974; Rice and Claypool, 1980; Lovley and Goodwin, 1988). It is important to note that aerobic metabolism may occur also in porous rocks at greater depth where hydrodynamic conditions allows influx of oxygenated, meteoric water. This is the condition that allows aerobic, bacterial degradation of petroleum in a reservoir.

SEDIMENT DIAGENESIS

Chemical diagenesis in sediments includes authigenic mineral precipitation, replacement, and solution.

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Table 4. Classification of bacteria according to energy source and source of nutrition (carbon)

Bacteria	Energy source	Carbon source
Autotrophs	Photosynthesis (light energy)	CO_2
	Chemosynthesis (oxidize inorganics)	CO_2
Heterotrophs	Oxidation (oxidize organics)	Organic compounds (some use CO_2)

Bacterial processes can play a major role in diagenetic reactions involving not only organic materials, but inorganic mineral phases as well. These processes are important in petroleum systems because they can affect reservoir properties.

In general, bacterial metabolism under anaerobic conditions increases pore water alkalinity and decreases Eh. In the sulfate-reducing zone, SO_4^{2-} (sulfate), HS^- (sulfide), and HCO_3^- (bicarbonate) are among the most important dissolved species (Claypool and Kaplan, 1974; Goldhaber and Kaplan, 1974). In the methanogenesis zone, CH_4 and H_2 are among the most common dissolved species. Precipitation of iron sulfides and carbonate minerals are common diagenetic effects of accumulation of bacterial end-products in pore waters. Additional bacterial processes of importance in diagenesis are iron and manganese reduction (Aller and Rude, 1988; Lovley and others, 1987, 1988, 1989a,b, 1990; Lovley and Phillips, 1988). Iron, sulfate, and carbonate reduction are particularly important because these reactions affect pore water concentrations of species involved directly in mineral reactions. However, bacterial processes in general affect the pore water pH, Eh, and ionic strength even though the inorganic substrates may or may not participate directly in mineral diagenetic reactions. Therefore, mineral stabilities in pore waters of organic-rich sediments can be affected indirectly by bacterial activity.

PETROLEUM DEGRADATION

Bacterial degradation can significantly diminish the economic value of a petroleum accumulation because of increased recovery and refinery costs. In addition, bacterial alteration of petroleum can be so extensive that geochemical evaluation of thermal maturity, source correlation, and secondary migration becomes nearly impossible.

Effects of biodegradation of petroleum are summarized by Connan (1984) and references therein. According to Connan (1984), the requirements for aerobic biodegradation of petroleum include (1) moving water (meteoric), (2) oil-water contact since bacteria live in the aqueous phase, (3) supply of nutrients such as nitrogen and phosphorus, and (4) proper temperature (less than about 100°C).

FORMATION OF CRUDE OIL AND NATURAL GAS

Bacteria play important roles in the accumulation of sedimentary organic matter (formation of potential petroleum source rocks) and in generation of methane natural gas resources. In well-oxygenated sedimentary environments, oxidation of organic matter by aerobic bacteria contributes to poor preservation of organic matter of the type contained in effective petroleum source rocks (hydrocarbon-generating organic matter). Inhibition of aerobic decay by lower oxygen levels can contribute to preservation of better quality (more lipid-rich or oil-prone) organic matter. Harvey and others (1986) showed that degradation and mineralization of organic matter proceeds more rapidly under aerobic than under anaerobic conditions. Further, Harvey and others (1986) presented evidence that high organic carbon content in sediments inhibits bacterial degradation of lipids, so that in organic-rich sediments positive feedback may occur between preservation of large amounts of organic matter and depressed bacterial degradation of lipids.

It is important to note, however, that complete oxidation of organic matter is possible in anaerobic sediments by bacteria using nitrate, sulfate, iron, or manganese as the sole electron acceptor (Pfenning and others, 1981; Stams and others, 1985; Szewzyk and Pfenning, 1987; Lovley and Phillips, 1988). Other factors also affect preservation of organic matter, such as rate of organic productivity in the water column, sedimentation rate, sediment particle size, and bioturbation, but bacteria are clearly important components in the overall process.

Bacterial generation of gas is thought to account for about 20 percent or more of the world's resource of natural gas (Rice and Claypool, 1980). Methane generation is accomplished not by a single organism, but rather by a consortium of bacteria. Anaerobic bacteria produce extracellular enzymes that hydrolyze carbohydrates and proteins to produce simple sugars and amino acids. The sugars and amino acids are then converted to ketoacids (pyruvate), hydroxy acids (lactate) and fatty acids (formate, acetate, propionate), CO_2, and H_2. Proton-reducing bacteria convert protons to hydrogen gas, which in turn is used by the methanogenic bacteria as a reducing agent. Methanogenic bacteria reduce the CO_2 by reaction with H_2 or split acetate produced from the preceding reactions to form methane and CO_2.

The methanogens are a diverse group of bacteria that exhibit a wide tolerance of environments including virtually every habitat in which anaerobic degradation of organic matter occurs (Jones and others, 1983). Methanogens have been isolated from freshwater and marine sediments, and extreme environments such as geothermal springs and deep-sea hydrothermal vents (Huber and others, 1982; Jones and others, 1983). Methanogenic bacteria are most active at pH 6.5 to 8.0 and at temperatures of 4°C to 45°C (Zeikus and Winfrey, 1976). This "cosmopolitan" status of methanogens is attributable to their unique mode of metabolism (methane generation) and the fact that the compounds that serve as substrates are end products of other metabolic processes (Jones and others, 1983).

ROLE IN EXPLORATION

Besides their importance in sedimentary processes that form some rocks or reservoirs and in petroleum alteration, bacteria contribute biological marker compounds to sedimentary organic matter. These biomarkers are present in petroleum as well and can be useful indicators of thermal maturity and the depositional setting of the source rock or can be used for oil-source rock or oil-oil correlation studies to identify petroleum systems.

FURTHER WORK

A number of studies have demonstrated that bacteria thrive in both oxygenated and anoxic marine and freshwater sediments, and isotopic evidence indicates clearly that bacterial metabolites are involved in various mineral reactions. Despite these field studies and a number of laboratory studies in which bacteria have been studied under a wide range of growth conditions, considerable uncertainty remains with respect to constraints on bacterial activities in sedimentary environments. The principal limitations are certainly availability of nutrients, temperature, pH, Eh, osmotic pressure, toxicity of metabolic products, and competition among various bacteria for common substrates. The porosity, permeability, and hydrodynamic regime of a particular setting are also important because these factors influence the growth factors listed above. However, the precise interplay of these factors with respect to either individual or cumulative bacterial processes is imperfectly understood. Improved understanding of the ecological requirements of various bacterial communities and their effects on the accumulation and composition of sedimentary organic matter is important for correlations and source-rock studies in petroleum systems.

The depth in a sedimentary basin over which bacteria remain active or viable is poorly established. Methanogens are known to remain active at temperatures as high as 85°C (Postgate, 1984) if other suitable growth factors are present, and some sulfate-reducing bacteria have been reported at 100°C (Stetter and others, 1987). Another question is whether bacteria remain viable, even though inactive, during relatively deep burial (accompanied by high temperatures) so that when erosion occurs and the environment becomes more hospitable bacterial growth might be revitalized.

Inorganic computer models of diagenetic reactions leave out possible effects of bacterial processes. Bacterial processes could introduce a large uncertainty into these models because metabolic pathways sometimes favor reactions (via coupled or multiple biochemical pathways) not predicted by thermodynamics. These bacterial processes could dramatically affect the pore water composition during early diagenesis in an unpredictable manner. Furthermore, as discussed previously, pore water Eh and pH can be significantly shifted by bacterial metabolism. Therefore, computer models of mineral diagenesis in organic-rich sediments need to allow for compositional changes in reactions mediated by bacteria.

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Coalbed Methane

By Ben E. Law[1]

INTRODUCTION

Estimates of coalbed methane resources in-place in the United States range from 72 to 860 trillion cubic feet (tcf), with most estimates ranging from 300 to 500 tcf (Rightmire, 1984). Cumulative gas production from coal beds through January 1991 was about 400 billion cubic feet. Commercial coalbed gas production in the United States began in about 1977 from the San Juan basin of New Mexico and Colorado and the Black Warrior basin of Alabama. Since 1989, gas production has expanded into the Piceance basin of Colorado, the Powder River basin of Wyoming, and the Cherokee basin of Kansas. In the Raton basin of Colorado and New Mexico, gas production is awaiting pipelines, and in the northern Appalachian region, where a few coalbed gas wells have been producing gas since the 1940's, the issue of gas ownership is a large obstacle to exploration and production. Additional areas with production potential, such as the Green River basin of Wyoming, have been hampered by environmental problems related to water disposal.

Internationally, there is a growing interest in coalbed methane as an energy source. Exploration for coalbed methane has been initiated in Canada, Australia, China, Russia, and several European countries. Ironically, in some of these countries activity has been spurred by a desire to alleviate environmental problems associated with coal mining and the direct utilization of coal.

The continued expansion of coalbed methane exploration and production into additional coal-bearing regions will require an improved understanding of these accumulations, as well as favorable economic conditions. Nearly all of the current research in the United States is in the Black Warrior and San Juan basins, where there is an emphasis on engineering and production aspects. The geologic variables that have been determined to be important in coalbed-methane accumulation and production include rank, pressure, temperature, permeability, and moisture. Although the roles of these geologic criteria are known in a general way, there is a need to determine the relative importance of these variables in different coal-bearing basins.

RANK

It is well known that gas content increases with increasing coal rank (Juntgen and Karweil, 1966; Meissner, 1984). Low-rank coals (lignite through high-volatile C bituminous) contain as much as 80 standard cubic feet per ton (scf/ton), whereas higher rank coals contain as much as 700 scf/ton. The gas in low-rank coal is usually biogenic and gas in high-rank coal is thermogenic. Low-rank coals are usually normal or under-pressured and high-rank coals are commonly over- or underpressured. In areas of high-rank coals, such as the San Juan basin, economically recoverable gas accumulations are pervasive and are independent of structural and stratigraphic traps. Since most coal-gas research has been conducted in high-rank coals, there is some uncertainty regarding the nature of coalbed methane accumulations in low-rank coals. Additional research is needed to more accurately determine the relationships among coal rank, gas generation, gas content, and gas composition.

PRESSURE AND TEMPERATURE

The amount of gas contained in coal of a given rank is related to pressure and temperature (Juntgen and Karweil, 1966; Meissner, 1984); with increasing pressure, gas content increases and with increasing temperature, gas content decreases. In general, overpressured coals are more productive than normal or underpressured coals, and it is usually necessary to reduce formation pressure to initiate gas production.

Current research is mainly on engineering aspects of pressure that include refining methods of measuring the adsoption capacity of coal and the effects of confining pressure on coal permeability. Geologically, there are only a few pressure and temperature studies related to coal-gas (Meissner, 1984; Kaiser and others, 1991).

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Additional research is needed to examine and relate the pressure and temperature histories of coal to present-day conditions.

PERMEABILITY

The principal permeability pathway in coal is through the cleat system (fractures). The cleat system in coal is defined by an approximately orthogonal set of fractures referred to as face and butt cleats. Face cleats constitute the dominant set and butt cleats the subordinate set. Due to the better development of face cleats, permeability in coal commonly exhibits varying degrees of anisotropy, with the better development parallel to the face cleat direction. In the absence of effective cleat permeability, economic levels of gas production from coal beds would be impossible.

The origin of cleats is unknown, although hypotheses have been made that include tectonic deformation, shrinkage due to moisture loss, and extension related to the relaxation of stress (Moore, 1922; Price, 1966; Ting, 1977). The factors that are known to affect the characteristics of cleats include bed thickness, coal quality (ash and maceral content), rank, and tectonic deformation (Macrae and Lawson, 1954; Ammosov and Eremin, 1960; Ting, 1977). While these studies and more recent basinwide studies in the Piceance and San Juan basins (Grout, 1991; Tremain and others, 1991) facilitate characterization of the cleat system, they do not necessarily characterize the permeability of cleats under in situ confining pressures; at depth, permeability may be ineffective due to high confining pressures and a closed cleat system.

MOISTURE

One of the largest obstacles to economic recovery of coalbed methane is water. The presence of water inhibits desorption of gas from the coal and flow to the wellbore (Joubert and others, 1973). Consequently, coal beds are commonly dewatered to a point at which gas begins to desorb from the matrix. The period of time necessary to accomplish sufficient dewatering is highly variable and in some cases is never reached. The success of dewatering efforts depends on development of the cleat system and on the source of water, which may be from recharge at the outcrop, from adjacent aquifers, or from inherent moisture in coal. In those cases where the source of water can be determined, the feasibility of a dewatering program can be evaluated more objectively. However, current methods of determining the source of water are unreliable.

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Turbidity Current Processes

By William R. Normark[1] *and* David J.W. Piper[2]

INTRODUCTION

Generalized facies models for turbidite deposits provide only a first-order interpretation of the detailed evolution of turbidite sequences and their relationship to sea-level fluctuations and source-area tectonism. A more powerful approach is to analyze a turbidite depositional system in terms of its sediment source, the processes controlling initiation of turbidity flows, how the resulting turbidity currents evolved during flow, the relation of flow characteristics to morphologic development of both the pathway(s) and depositional areas, and how these flows relate to depositional facies.

Although our understanding of flow processes has been hampered by the difficulty of direct observation or monitoring turbidity currents at sea, recent advances in both field observation and numerical modeling indicate that the variety of turbidity-current flows has been underestimated in the past. An increasing body of evidence shows that many, if not most, recognizable turbidites were deposited from quasi-steady flows that last for many tens of hours. This conclusion is radically different from the catastrophic, high-density surges (volume concentration as much as 6×10^{-1}) envisaged by earlier workers (Kuenen, 1950; Heezen and Ewing, 1952). Bagnold (1962) showed that grain-to-grain collisions prevent turbulent transport of sediment above sediment concentrations of 9×10^{-2} (volume concentration). Recent work further shows that much of the sediment transport takes place in flows with sediment concentrations that are well below this limiting value or that approach it only near the base of the flow.

Pertinent research from the last two decades (see review in Normark and Piper, in press) that exemplifies the broad range in the character of turbidity currents is summarized in three sections that reflect both the nature of the data and the degree of change in our understanding of the processes and products of these currents. These sections are (1) initiation processes, including fluid-flow and sediment-failure mechanisms; (2) the flow of turbidity currents in channels, recognizing that the channel properties reflect a rather limited range of flow conditions that might exist within any given turbidite system; and (3) inferences of flow processes from the deposits left by turbidity currents. This review concludes with the implications for facies distribution in the resulting turbidite deposits. Figure 6 and the expanded reference section parallel the text organization.

INITIATION

Significant new insights on processes that generate sustained turbidity currents have come from studies of flows generated by the injection of concentrated sediment suspensions that result either from river discharge or storm surges, and flows that evolve from mass failures on deltaic and basin slopes. Both the grain-size distribution and the volume of material available to form a turbidity current reflect the primary source area and the effects of any intermediate staging areas where sediment may temporarily accumulate before being remobilized. In addition, flow characters such as the speed, thickness, and sediment distribution within the flow itself reflect the source characteristics. Figure 6*A* shows our understanding of the relation between initiation processes for turbidity currents and sediment input parameters. Differ-

Figure 6. Schematic representation of the principal factors controlling initiation, transport, and deposition in turbidite systems (developed from figures in Normark and Piper, in press). *A*, Typical total sediment volume and petrology/grain-size distribution for various types of flow initiation. *B*, Principal processes acting during channelized phases of sediment transport. Cross section shows general characteristics of sandy, mixed, and muddy turbidity currents; note that each of these types can show great variation in total size and thus flow thickness and duration. *C*, Typical sediment deposits resulting from different types of flow in a simple channel/levee system leading to a depositional lobe.

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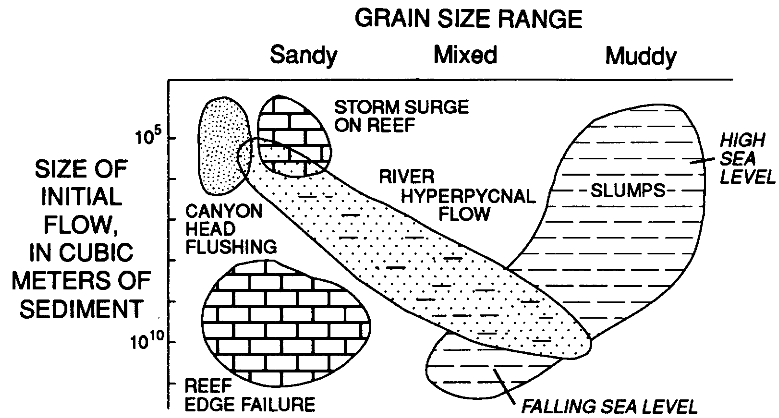
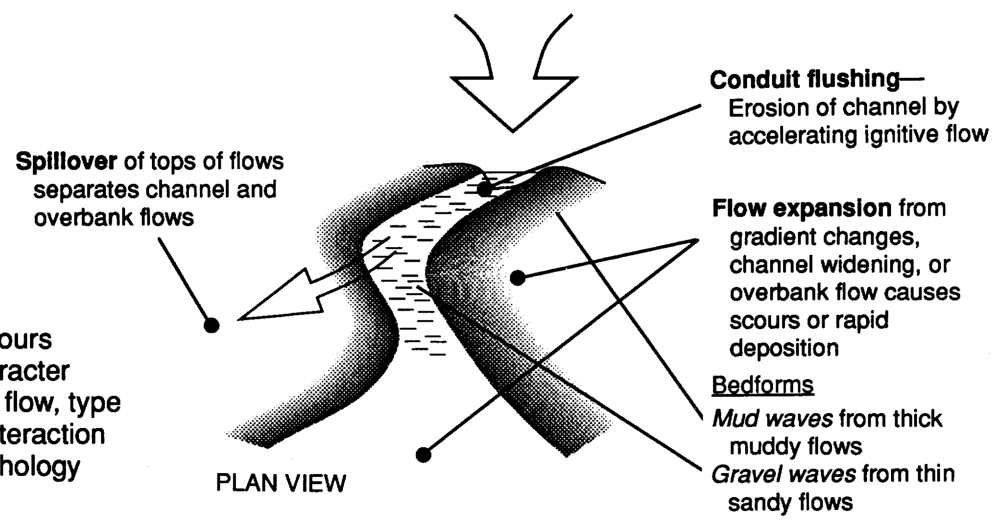
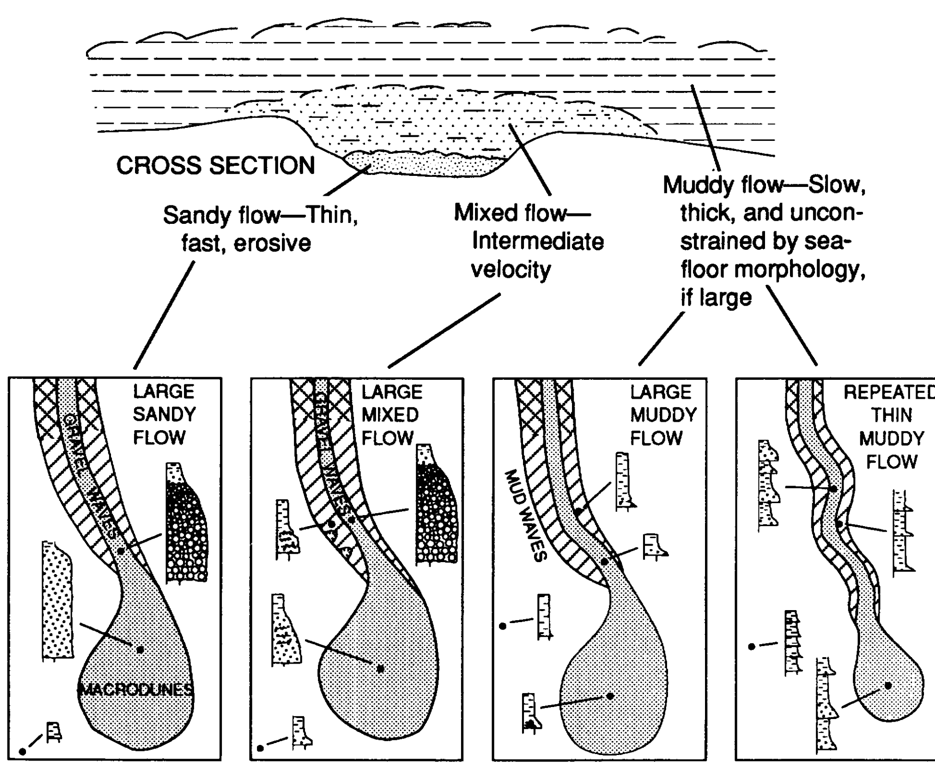
A
Initiation requires a steep slope and a process to suspend sediment



B
Transport of many hours duration. Flow character depends on size of flow, type of sediment, and interaction with sea-floor morphology



C
Deposition patterns result from flows of different grain size, thickness, and velocity interacting with pre-existing morphology



ent initiation processes involve different volumes and grain-size compositions and reflect the local geographic settings. Turbidity currents from reef-edge failures are generally much smaller but with a larger proportion of coarser sediment than those generated by failures on passive-margin slopes (fig. 6*A*).

Initiation by River Discharge

The direct, or hyperpycnal, flow of turbid rivers and tailings discharge into lakes has long been known to result in turbidity currents (Gould, 1951; Lambert and others, 1976; Normark and Dickson, 1976; Weirich, 1984). For a turbidity current to develop from an initial suspension flow, the suspension flow must maintain a sufficient velocity (through inertial effects or external forcing) until there is a sufficient gradient for a turbidity current to be self-sustaining. Experimental studies and observations of flows into lakes and fjords have identified those conditions in which the gradient and suspended sediment concentration are sufficient for the turbidity-current flow to accelerate. Under these conditions, the flow can erode and put more sediment into suspension, thus providing additional power to the current. This positive feedback situation is referred to as "ignition" (Parker, 1982).

Initiation of Currents by Storms

Ignitive flow of coastal sand down submarine canyons has been documented where rip currents associated with storm surges catastrophically remove sand from canyon heads (Fukushima and others, 1985). This mechanism is potentially significant wherever there is a narrow shelf and canyons intersect the littoral-drift system; thus, such environments would have been more common during Pleistocene low stands of sea level.

Data from a suite of displaced current-meter moorings indicate that turbidity currents formed as a result of a storm surge across a reef front related to the passage of Hurricane Iwa through the Hawaiian Islands on 23 November 1982 (Dengler and others, 1984a,b). Carbonate turbidites and debris flows are common along carbonate margins, and many adjacent basinal turbidites show multiple entry points (Mullins, 1983), consistent with a storm-surge trigger for the flows; the data do not exclude, however, initiation resulting from seismic shaking.

Sediment Failure Initiation Processes

Most turbidity currents are commonly thought to result from seismically triggered mass failures, but there are remarkably few studies that document the relation between sediment failure and turbidity-current flow. Some of the issues involved in the seismic initiation of turbidity currents are more clearly defined from recent studies of the 1929 Grand Banks turbidity current. The 1929 event on the Laurentian Fan off eastern Canada has long been regarded as a type example of a catastrophic, seismically triggered turbidity current (Heezen and Ewing, 1952; Heezen and others, 1954). Numerous authors (the earlier ones reviewed by Menard, 1964; the more recent ones by Kirwan and others, 1986) have attempted to model the flow as a surge, but this is inconsistent with the evidence for prolonged and quasi-steady flow provided by the regular gravel bedforms and scours on the valley floor and by the sediment-flux requirements (Hughes Clarke and others, 1990). Failure did not take place in a single large slide; rather, there were numerous shallow slides, separated by less disturbed areas of seabed. Hughes Clarke (1988) argued that to maintain flow over a period of several hours, there must have been a continuous process of transformation of debris flows to turbidity currents. Silty sediment put into suspension following widespread slope failure could have flowed ignitively (Piper and others, 1991). The convergent valley pattern on the slope above the Laurentian Fan would aid in the concentration, maintenance, and acceleration of such ignitive flow.

Turbidity currents triggered by large earthquakes may be recognized from their synchronous development in several different drainage basins (Adams, 1989; Anastasakis and Piper, 1991). In ancient basin-plain sequences, amalgamated beds may be evidence of large seismically triggered turbidity currents. Earthquakes are not the only triggers for failure of upper-slope sediment, where failure also may be induced by storm waves. Not all failures, however, will result in ignitive flow producing turbidity currents.

Turbidity Current Initiation on Deltas

Because sediment strength and seabed slope are important in determining whether sediments fail, rapidly accumulating deltaic sediment, which tends to be underconsolidated and has relatively low strength, is particularly susceptible to failure, especially where the deposit is prograding across steep slopes. Such deltaic environments also may be the site of hyperpycnal inflow of sediment-laden river discharge that can form a turbidity current directly. The high sediment concentrations associated with high-bedload-discharge rivers suggest that they may be the most likely to initiate turbidity currents. Recent case studies of fjord deltas off British Columbia and Baffin Island, Canada, provide our best evidence to date to evaluate hyperpycnal flow and slumping mechanisms for generating turbidity currents (Prior and others, 1981, 1982, 1986, 1987; Syvitski and Hein, 1991; Syvitski and others, 1987).

TRANSPORT

Turbidity currents vary in the total amount of sediment transported, duration, grain-size distribution of transported sediment, velocity, and thickness. Smaller currents tend to deposit their load in more proximal environments; larger currents may transport sediment to distal environments. The morphology of deep-sea fan systems reflects the cumulative erosional and depositional effects of a large number of turbidity currents, each of which interacts with channel conditions in different ways. The volume of large turbidite beds cannot be equated directly to the volume of sediment released in a single initiating event; an accelerating large current may erode sediment from the floor of any conduits and transport substantial amounts of deep-water sediment, including that deposited by previous, probably smaller, currents.

Channel overflow, erosion of channel walls, lateral migration of channels, and large-scale depositional bedforms are just some of the features that provide insight to flow characters that can be used to deduce flow conditions (fig. 6*B*). Limited field evidence shows that turbidity currents that transport a large proportion of sand are thinner than those that are predominantly of mud and also that there is a vertical gradient in the grain size of sediment transported by a turbidity current. These two general trends are a consequence of the dynamics of turbidity-current flow and are accentuated by entrainment of water at the top of the flow and erosion of sediment under ignitive conditions at the base. They are confirmed by flume experiments (Parker and others, 1987) and can be predicted by physical modeling (Stacey and Bowen, 1988a,b).

Different flows react in different ways to sea-floor relief (fig. 6*B*). A small flow may be confined within a fan valley system; a larger flow may be essentially channelized, but spill over the levees (Hay, 1987b). Thick flows may experience flow-stripping of the upper part of the flow at abrupt bends in the channel (Piper and Normark, 1983), and a very thick flow may move downslope with the fan valley acting merely as a local roughness element (in cases where the flow thickness greatly exceeds the channel depth).

The role of the Coriolis force, which is a geostrophic effect of the Earth's rotation that is proportional to latitude and flow velocity, also reflects flow characters. Slow, muddy turbidity currents that exceed channel relief can develop a significant cross-flow gradient affecting deposition throughout the basin; the effect of thin, fast, sandy flows in controlling deposition is more pronounced immediately downslope from the channel termination zone.

On mature passive-margin fans such as the Amazon and the Mississippi, there are highly sinuous fan channels with continuous levees (Flood and Damuth, 1987; Kastens and Shor, 1985). Such channels appear in equilibrium with bankfull or smaller flows: there is no evidence for slightly larger flows that would be expected to breach levees on sharp bends, although the possibility of very thick flows oblivious to channel relief cannot be excluded. This suggests that flows are relatively slow, hence of relatively low density and long duration. Turbidity currents initiated by seismic failure (such as the Holocene deposits of Navy Fan and Cascadia Channel), or by bedload delta processes such as hyperpycnal flow or mouth-bar failure (such as Var Fan, late Pleistocene deposits of Navy Fan) appear to be much more variable in size, and variably erode or deposit on different parts of the fan system, thus yielding a more complex morphology (Piper and Normark, 1983; Savoye and Piper, 1990).

The deposition of sediment waves on levees (Normark and others, 1980) requires flow thicknesses substantially greater than channel depth, in order that channel processes do not interfere with the uniformity and continuity of the sediment waves.

DEPOSITION

Flow Processes Implied from Turbidite Bedforms

Bedforms in turbidite systems provide evidence for the importance of prolonged turbulent fluid flow in the deposition of turbidite beds. They also have the potential for providing quantitative information on the characteristics of the flow, as has been done in studies of fluvial flow. Large-scale scours within turbidite deposits are, perhaps, the prime example of features that went unobserved because of their scale; in outcrop studies, erosional features of this size are generally misidentified as channels (Mutti and Normark, 1987). All of the scour examples referenced occur in, or immediately downslope from, areas of the turbidite deposits where the fan or channel gradients indicate that flows could be supercritical using layer-averaged flow models. In addition, all occur in areas within or downslope from regions where rapid flow expansion is implied, associated with an increased turbulence within the flow.

The imaging of many deep-sea fans by sidescan sonar systems in the last decade has shown that coarse fan-valley and lobe sediments have a variety of large-scale depositional bedforms. These include gravel waves, whose wavelength may be a measure of bed shear stress (velocity), and regular, large-scale sediment waves developed in predominantly fine-grained sediments (principally on levees) and for which the significance of size variation is poorly understood.

Implications for Facies Distribution in Turbidite Systems

The variability in source materials, initiating processes, and flow characteristics of turbidity currents leads to corresponding variability in deposits (fig. 6*C*). The architectural element approach, originally developed for fluvial systems (Miall, 1985), has more recently been applied to turbidite systems (Mutti and Normark, 1987). The **channel** element is a site of both erosion by fast ignitive flows, in part through large scours, and rapid deposition from smaller flows that have lost their upper parts by flow stripping. Ultimate preservation depends on base-level fluctuations and fan aggradation. On **levees**, flow expansion of smaller overbank flows leads either to erosion or to irregular deposition; thicker, muddy flows lack significant flow expansion across the levee and deposit uniform silty muds, in some cases associated with large-scale mud waves.

Smaller muddy and mixed flows undergo flow expansion at the end of a channel-levee system, depositing on a small **lobe** that may aggrade steadily and be prograded over by the channel-levee system. Larger sandy flows tend to erode proximal lobe deposits, and thick muddy flows generally undergo little modification in passing through the channel-lobe transition zone.

The deposition of sediment on distal parts of turbidite systems is very dependent on upstream flow behavior of turbidity currents: the majority of turbidity currents in a system never reach the distal part of a basin (Piper and Normark, 1983). It is only the very large flows that control the accumulation of distal fan sediment. Vertical flow expansion resulting from gradient changes probably provides the major control on deposition (Piper and Stow, 1991).

Allocyclic Changes In the Basin

The role of eustatic sea level change is to alter the types of flow-initiation process and hence the types of turbidity currents flowing into a basin. Falling sea level, if accompanied by fluvial incision, may promote hyperpycnal flow of turbidity currents into basins; if canyon incision occurs, the resulting increase in local slopes may trigger slumps and promote ignitive flow processes and conduit flushing, leading to mixed or muddy flows of variable size. Eustatic low stands provide the time of maximum direct input of fluvial sediment, which in sandy fans leads to flushing out of the channel systems. During rising sea level, seismic triggering of flows predominates, resulting in some thick muddy flows (fig. 6*C*).

Sea-level changes may also influence coastal morphology, so that the locus of sediment supply is changed. For example, the northern Ascension Canyon source for Monterey fan intercepts littoral-drift sediment at low stands of sea level, but during high stands, this canyon is bypassed and sediment is intercepted primarily by the more deeply incised Monterey Canyon itself (Hess and Normark, 1976). On Navy Fan at times of lowered sea level, the Tijuana River supplied sediment directly to the canyon head that leads to the fan whereas during high stands, this sediment was trapped on the shelf and the only turbidity currents to reach the fan result from seismically triggered failure of older prodeltaic sediments (Piper and Normark, 1983).

Tectonic Settings of Turbidite Sequences

The concept of variation in source material and type of turbidity current in determining basin architecture permits a broad classification of turbidite sequences.

1. Young passive-margin systems with a narrow shelf and steep gradients have a dominance of sand supply. Rapid progradation of delta-mouth sediment leading to oversteepening, possible hyperpycnal flow of sandy river bedload, and seismic triggering of prodeltaic slides are likely on such margins, yielding mostly small turbidity currents of rather sandy composition (fig. 6*A*).

2. Mature passive-margin systems have low sand-to-mud ratios in their sediment supply, and fan morphology suggests that hyperpycnal flow from rivers is important in fan evolution, yielding uniform low-velocity flows that steadily build narrow levees that prograde over uniformly aggrading lobes. Sea-level changes predominate in triggering sediment failure; the resulting very large flows lead to basin aggradation.

3. Active-margin systems resemble those of young passive margins but may have a more mature fluvial supply and a greater proportion of mud. Steep slopes and large magnitude earthquakes lead to seismic triggering predominating, at least during eustatic high stands: resulting turbidity currents tend to be large and of variable composition.

4. Carbonate-margin systems receive sediment both from catastrophic failure of reef fronts and from storm-driven flows across the shelf break. The latter may lead to more stable channel systems that may be occupied by mixed clastic-carbonate turbidity currents at low stands of sea level. Shelf-break failure results in aprons of debris-flow deposits with thin distal fine-grained turbidites lacking well-developed channels.

SUMMARY

Predictive stratigraphic analysis of deep marine basins requires an understanding of the processes through which individual turbidity currents interact with and modify basin physiography. Overall basin shape and size are principally a consequence of regional tectonism, but many of the morphologic features that control turbidite depositional patterns result from the erosional and depositional effects of previous turbidity currents. The steady flow of turbidity currents over tens of hours interacts in a predictable way with basin physiography. The character of these flows depends on the nature of the sediment, the initiating process(es), and the physiographic setting in the source area. These parameters can be stochastically predicted from a knowledge of source-area tectonics, climate change, and eustasy.

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Porosity

By James W. Schmoker[1]

The discussion of porosity presented in this forum two years ago by Schmoker and Gautier (1989a) noted that, although porosity has often been inversely correlated to burial depth, plots of porosity versus thermal maturity offer an alternative to the prediction of porosity change during burial that may better integrate effects of burial history upon porosity modification. The present discussion reviews the growing body of literature dealing with relations between porosity and time-temperature exposure (thermal maturity).

The idea that porosity change in the subsurface is controlled in part by time-temperature exposure has been present in the literature for some time. Maxwell (1964), working with a large body of data, found temperature to be an important variable affecting porosity loss in quartzarenites during burial. Maxwell also noted that time played a role in porosity modification because, all else being equal, older rocks in his data set tended to have lower porosities. The earliest reference I have found that specifically links porosity evolution in the subsurface to time-temperature exposure is an abstract by van de Kamp (1976). Lyons (1978, 1979) and Cassan and others (1981) expanded upon the idea that the porosity of sedimentary rocks can be advantageously considered in terms of thermal maturity. McCulloh and others (1978) reviewed processes of burial diagenesis affecting the porosity of clastic rocks and emphasized the importance of temperature upon most of these processes. They envisioned a certain order and predictability behind the complex details of porosity modification during burial, likening the typical net loss of porosity to the progressive alteration of kerogen with increasing thermal maturity. Siever (1983) regarded integrated time-temperature history as the relevant parameter for subsurface reaction kinetics.

Schmoker (1984) presented data indicating that porosity loss in carbonate rocks can be empirically represented as a function of integrated time-temperature history. Dixon and Kirkland (1985) investigated sandstones in relatively young basins of southern California and found that the porosity of these rocks can be correlated with the thermal gradient. In laboratory experiments, Porter and James (1986) found that temperature had a significant influence on quartz solubility and thus on pressure solution.

Within the last few years, studies describing porosity change in terms of integrated time-temperature history have become more common in the literature. Ehrenberg (1987) and Harris (1988) reported that porosities of Jurassic sandstones of the North Sea depend strongly upon thermal maturity. Bloch and others (1990) observed that porosity of the Mississippian Kekiktuk Formation of the North Slope of Alaska can be better predicted as a function of integrated burial history than of depth. Earlier, van de Kamp (1988) had linked the porosity of Ellesmerian-sequence sandstones of the North Slope (Carboniferous to lowermost Cretaceous) to thermal maturity as represented by vitrinite reflectance. Surdam and others (1989) and Jansa and Noguera Urrea (1990) discussed organic/inorganic reactions and consequent porosity change in terms of thermal maturity.

The common thread running through the diverse set of references cited is that porosity change in the subsurface results from processes that can be advantageously treated as functions of time-temperature exposure.

Porosity decrease in the subsurface was represented by Schmoker and Gautier (1988, 1989b) and Schmoker and Hester (1990) as a power function of time-temperature exposure:

$$\phi = A(M)^{B}, \quad (1)$$

where ϕ is porosity, A and B (a negative number) are constants, and M is a measure of integrated time-temperature history. This equation treats porosity as evolving through time and responding to changes in temperature even if depth is unchanged.

The practical problem exists of how best to numerically represent time-temperature exposure (M) in relations such as equation 1. The ideal index would closely reflect the kinetics of porosity-affecting processes, but such an index is unknown and is unlikely to be developed in the near future because of the great diversity of subsurface processes.

[1] U.S. Geological Survey, Denver, Colo.

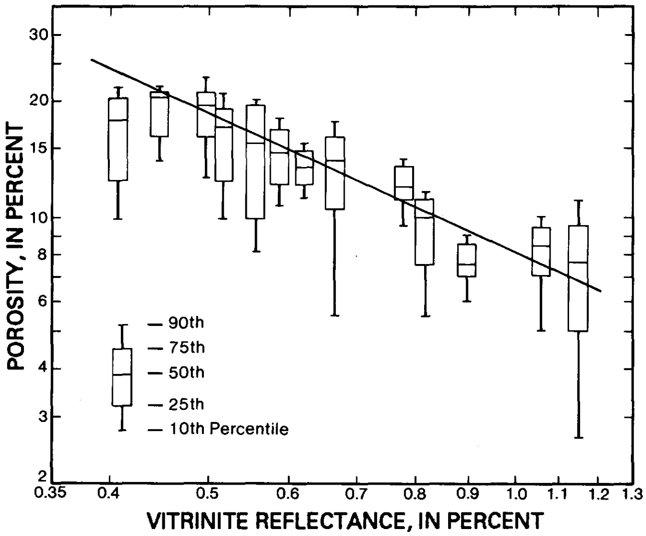

Figure 7. Sandstone porosity versus vitrinite reflectance (R_o) illustrating power-function relation of equation 1. Regression line is fit to median porosity (50th porosity percentile). Data represent Lower Cretaceous J sandstone of Denver basin (from Schmoker and Hester, 1990).

A number of indices measuring time-temperature exposure have been put forward in connection with kerogen maturation. Among these, Lopatin's time-temperature index of thermal maturity (TTI) (described by Waples, 1980) and vitrinite reflectance (R_o) are probably the best known of the mathematical and laboratory indices, respectively. TTI and R_o have been used in porosity models as convenient if somewhat imperfect measures of *M*.

The use of TTI and R_o in the context of porosity prediction does not necessarily imply that porosity change is causally related to kerogen maturation. In the broader sense, TTI and R_o are simply general measures of time-temperature exposure. However, because TTI and R_o are commonly used to define stages of hydrocarbon generation, relations such as equation 1 can serve to place porosity change and petroleum generation in a mutual context.

Plots reproduced here of sandstone porosity versus R_o (fig. 7) and carbonate porosity versus TTI (fig. 8) are of typical data sets and illustrate the correlation between time-temperature exposure and porosity change in the subsurface. The range of porosities about the regression lines of figures 7 and 8 is shown by box diagrams. Such porosity variability is common and probably is due to geologic heterogeneity within the rocks under consider-

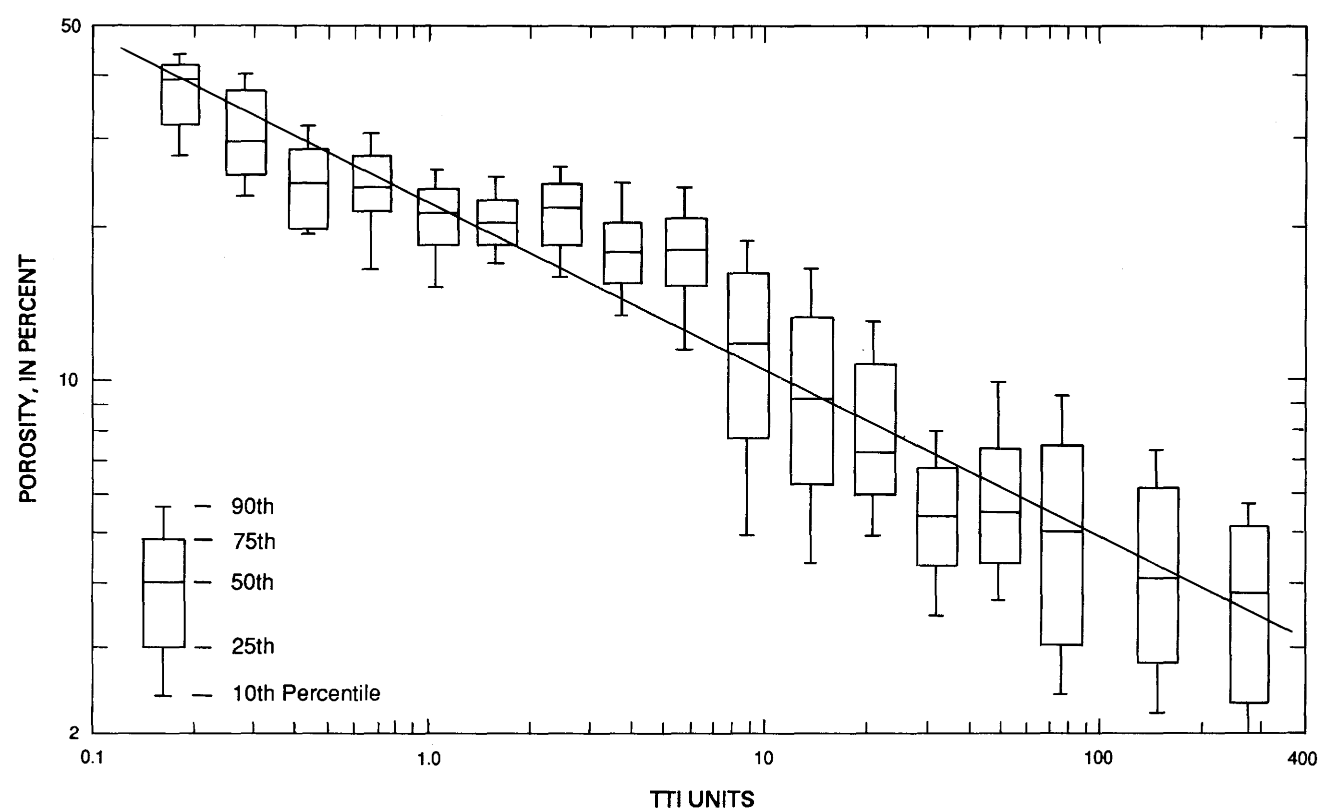

Figure 8. Carbonate porosity versus Lopatin's time-temperature index (TTI) illustrating power-function relation of equation 1. Regression line is fit to median porosity (50th porosity percentile). Data represent Lower Cretaceous to Eocene limestones and dolomites in 15 wells of South Florida basin (from Schmoker and Gautier, 1989b).

ation. Research on relations between porosity variability and localized geologic heterogeneity, as well as on details of the particular subsurface processes responsible for generalized porosity-maturity trends such as are shown in figures 7 and 8, is likely to be active in the next several years.

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Facies, Permeability, and Heterogeneity in Sandstone Reservoirs

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INTRODUCTION

The seven principal types of siliciclastic sandstone reservoir heterogeneity are related to (1) sandstone body geometry, (2) mudstone baffles to fluid flow, (3) facies and facies associations, (4) sedimentary structures, (5) laminae, (6) diagenesis, and (7) fracturing (Weber, 1986; Schenk, 1988). The purpose of this paper is to review current research on heterogeneity related to facies architecture of sandstone reservoirs (third type of heterogeneity) and the relation of architecture to patterns of permeability.

Architecture, defined as the patterns of facies that make up the internal construction of a reservoir, largely controls fluid flow in a reservoir because flow parameters such as permeability are strongly facies dependent. A knowledge of fluid flow patterns in a reservoir sandstone is required for successful field development, secondary and enhanced hydrocarbon recovery operations, and determination of hydrocarbon recovery factors (Tyler and Finley, 1989; Weber and van Geuns, 1990). Permeability measurements by facies are becoming an integral component of architectural studies of reservoir sandstones (Chandler and others, 1989; Dreyer and others, 1990).

The objective of analyzing sandstone architecture is to determine the spatial distribution and geometry of facies in a reservoir sandstone. Facies analysis can be done using outcrop or borehole log and core data, but for detailed examination of lateral facies transitions and facies geometry outcrops are essential, but not always available. Lateral profiling of outcrops documents the scales, types, complexity, and patterns of sandstone architecture that may be encountered or predicted in the subsurface (Miall, 1988, 1989).

Detailed studies of the lateral and vertical juxtaposition of sandstone facies, combined with permeability data by facies, provide realistic input to numerical models for reservoir simulation (Hearn and others, 1986; Krause and others, 1987; Ravenne and others, 1989; van de Graaff and Ealey, 1989). Facies comprising the major depositional environments are well known (Walker, 1984a), but more quantitative data are needed on the geometries of sandstone facies and the scale over which measured permeabilities are valid in sandstone reservoirs.

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EOLIAN SANDSTONE RESERVOIRS

Eolian sandstone reservoirs can be broken down into eolian dune (dune foreset and bottom-set), interdune, clastic sabkha, and sand sheet facies. Eolian-dune deposits are present in most sandstones recognized as eolian and are the most common petroleum-producing facies. The proportions of the other four facies vary considerably.

Studies of permeability by facies in eolian sandstones have documented that eolian-dune foreset sandstones have the highest permeabilities whereas dune bottom-set, interdune, and sabkha sandstones have the lowest permeabilities (Andrews and Higgins, 1984; Weber, 1987; Lindquist, 1988; Chandler and others, 1989; Krystinik, 1990).

Permian sandstones in the upper part of the Minnelusa Formation in the Powder River Basin, Wyoming, contain eolian-dune and clastic-sabkha deposits, but sand-sheet and interdune deposits are absent (Fryberger and others, 1983). The predominance of eolian-dune sandstone in the producing horizons make these Permian sandstones a relatively simple matter to develop and produce (Jorgensen and James, 1988). Permeability contrast within this sandstone is mainly between eolian ripple and avalanche strata.

In contrast, the Jurassic Nugget Sandstone in the Overthrust Belt of Wyoming and Utah contains eolian-dune, interdune, and clastic-sabkha deposits (Lindquist, 1988). The eolian-dune sandstones produce oil, but these sandstones are separated by nonproductive interdune and clastic-sabkha sandstones, making development and enhanced recovery difficult (Lindquist, 1988; White and others, 1990). Permeabilities between eolian-dune and interdune or sabkha sandstones can vary by several orders of magnitude. Prediction of the lateral distribution and vertical arrangement of nonproductive and productive facies in the Nugget Sandstone, along with the distribution of fractures, greatly assists in determining the proper method of field development and reservoir stimulation procedures (Krystinik and Schenk, 1989).

Eolian-dune sandstones of the Jurassic Norphlet Formation at Hatter's Pondfield, Mobile County, Alabama, exhibit facies-related permeability variations (Mancini and others, 1990) similar to those in the Nugget Sandstone; eolian-dune sandstones have the highest permeabilities, interdune sandstones the lowest, and sand-sheet sandstones slightly higher than interdune sandstones.

FLUVIAL SANDSTONE RESERVOIRS

Facies of fluvial deposits have been defined and described in many studies (Allen, 1978, 1983; Miall, 1978, 1988; Miall and Turner-Peterson, 1989), and the complexity of fluvial facies associations is well known.

Walton and others (1986) divided fluvial sandstones of the Cherokee Group (Pennsylvanian) into five facies. Permeability is correlated to these facies, and the juxtaposition of facies has produced a strongly layered reservoir with respect to fluid flow. Cross-stratified channel sandstones have the highest permeabilities, but permeability in all facies was a function of compaction and clay content. Ebanks and Weber (1987) also demonstrated a strong correlation between facies and permeability in heavy-oil-bearing fluvial sandstones of the Cherokee Group in Missouri. Their study illustrates the extreme sedimentologic complexity of the fluvial reservoirs within the field, which would be difficult to unravel without the large number of wells with borehole logs and conventional core.

Ravenne and others (1989) mapped the three-dimensional architecture of fluvial sandstones along cliff exposures in England as an analog for Jurassic fluvial reservoirs in the North Sea. Reservoir simulation models were built from lateral profiles of large outcrops, dimensions of fluvial sandstone bodies were mapped, and permeability variations by facies were measured. This study is an excellent example of combining architectural and permeability data to produce an analog for actual reservoir simulations.

Atkinson and others (1990) measured permeability differences between several braided fluvial facies in sandstone reservoirs of the Ivishak Formation (Permian-Triassic), Prudhoe Bay field, Alaska. Here, the largest permeability differences were between fluvial and deltaic facies. In another study, Hastings (1990) found that fluvial-channel sandstones had higher permeabilities than fluvial channel margin sandstones in reservoirs of the Pennsylvanian Tyler Formation, North Dakota.

In a study of Statfjord reservoirs in the North Sea, Henriquez and others (1990) stressed the importance of describing quantitatively sandstone body morphology, facies architecture, and hydraulic connectedness in developing simulation models of fluvial reservoirs. They concluded that the available architectural data for fluvial deposits, including fluvial-channel thickness, width, length, and orientation, were a principal limitation to modeling fluvial reservoirs, in spite of the body of work available on fluvial deposits.

DELTAIC SANDSTONE RESERVOIRS

Deltaic sandstones are an important group of hydrocarbon reservoirs, but surprisingly few studies are available on the relationship between deltaic facies and patterns of permeability.

Moslow and Tillman (1986) identified 12 facies in gas-productive wave-dominated deltaic sediments in the Cretaceous Frontier Formation along the Moxa arch, Wyoming. Permeability was strongly controlled by facies. Distributary channel facies had the best combination of porosity and permeability and formed the best reservoirs. Clay content (determined petrographically) was a critical factor in whether a distributary channel sandstone was a reservoir or not. Although facies dimensions could not be measured with borehole data from widely spaced wells, the sedimentologic model developed from the facies associations led Moslow and Tillman (1986) to conclude that typical well spacings in the Moxa arch area would not contact all of the isolated distributary channel sandstones.

In Oklahoma, Boyer (1985) described six facies from fluvial-dominated deltaic sandstones in the Pennsylvanian part of the Springer Formation. Permeability in these deltaic sandstones strongly correlated to facies; proximal delta-front sandstones had the best combination of porosity and permeability. Other facies had higher clay and cement contents, resulting in poor fluid-flow properties.

Tillman and Jordan (1987) found a relation between facies associations and permeability in Permian deltaic sandstones in the El Dorado field, Kansas. Of the six facies associations, the distributary channel and the splay-beach associations had the highest permeability and porosity.

In a study of wave-dominated deltaic sandstones of the Brent Group in the North Sea, Scotchman and Johnes (1990) found that deltaic distributary channel sandstones had the highest permeabilities whereas delta-front and crevasse-splay sandstones had the lowest permeabilities.

INTERDELTAIC SANDSTONE RESERVOIRS

Facies of strand-plain and barrier sandstones are well known, consisting of sandstones from lower, middle, upper shoreface and foreshore environments (McCubbin, 1982; Snedden and Jumper, 1990). However, strand-plain sandstones can be associated with wave-dominated delta-front, distributary channel, delta fringe, crevasse splay, and fine-grained marsh and levee deposits (Tyler and Ambrose, 1985). The architecture of a strand-plain sandstone reservoir can be complex if constructed from these facies, but strand-plain sandstones in general make better reservoirs than deep-water or fluvial sandstones because of the general lack of mudstones or shale layers within the sandstone that impede fluid flow (Ambrose and Tyler, 1989).

In a study of barrier sandstones of the Cretaceous Muddy Sandstone, Bell Creek field, Wyoming, Sharma and others (1990) found that upper and middle shoreface sandstones had much higher permeabilities than lower shoreface and overlying valley fill sandstones. Barrier sandstones can also be intercalated with tidal-inlet fills, flood- and ebb-tidal deltas, estuarine sandstones, washover-barrier flat sandstones, and back-barrier eolian sandstones, and can be nearly encased in fine-grained deposits (Galloway and Cheng, 1985; Fryberger and others, 1988). The presence of tidal-inlet deposits serves to disrupt the continuity of the barrier sandstones, resulting in a semi-compartmentalized reservoir sandstone that would not have been predicted using a simple barrier model for the reservoir (Galloway and Cheng, 1985). Studies of facies-related permeability are needed for these types of reservoirs.

MARINE SHELF SANDSTONE RESERVOIRS

Marine shelf sandstone facies are known in detail (Walker, 1984b), particularly the Cretaceous shelf sandstones of Wyoming (Tillman and Martinsen, 1984; Jackson and others, 1987). Shelf sandstones typically form lens-shaped bodies encased in marine mudstones, although facies associations and interbedding of reservoir and nonreservoir rock may be complex (Borer and Harris, 1991). Facies of the sandstones range from clean, cross-stratified sandstone to bioturbated muddy sandstone. Hearn and others (1986) identified five facies in the Cretaceous Shannon Sandstone Member of Wyoming, similar to Shannon facies interpreted by Tillman and Martinsen (1984, 1987). Hearn and others (1986) found that the reservoir sandstone could be divided into five flow units based on groupings of permeability data. The boundaries of the flow units generally matched the facies boundaries, but the match was imperfect. The flow units based on permeability, together with facies distributions and sandstone body thickness, were used to develop a layered reservoir simulation model for enhanced oil recovery.

DEEP-WATER SANDSTONE RESERVOIRS

Deep-water sandstones deposited in submarine fan and related environments contain many of the same facies as fluvial deposits—channels, sediment gravity flows, lateral accretion deposits, fine-grained levee deposits, and laminated sand sheets—but the proportions of the facies may be quite different than in fluvial deposits (Normark, 1990). The abundance of fine-grained layers in deep-water environments suggests that more mudstone layers are present within each facies and that deep-water sandstone reservoirs may be more compartmentalized by mudstones than fluvial sandstones (Phillips, 1987; Ambrose and Tyler, 1989; Hall and Link, 1990; Kulpecz and van Geuns, 1990).

Scott and Tillman (1981) illustrated many examples of clay clasts and clay laminae that separate otherwise permeable beds of sandstone in the Stevens sand (Miocene), a subsurface unit in the San Joaquin basin, California. Clay-free medium- to coarse-grained channel sandstones form the best reservoir facies. Hall and Link (1990) also found that channel sandstones in Miocene turbidite reservoirs had higher permeabilities than sandstones of turbidite depositional lobe and channel/lobe facies. Berg and Royo (1990), in a study of Miocene turbidite reservoirs in the Yowlumne field, California, found that turbidite sandstones of the central channel facies had higher permeabilities than sandstones of channel margin and other facies.

SUMMARY

This review has illustrated some recent work relating facies to permeability in reservoirs representing several depositional environments. More studies are needed on the relation between facies, facies geometry, and permeability. In general, the architectural complexity of sandstone reservoirs increases as the sandstones assume channelized forms (that is, strand-plain and eolian sandstones are not as complex as fluvial sandstones, channelized submarine-fan sandstones, or valley-fill complexes).

Additionally, as the number of mudstone layers and lenses in the depositional system increases, the more potential reservoir sandstones are compartmentalized into discrete packages that may not be in fluid communication. Isolated reservoir pods will not be swept in a typical drilling pattern. Drilling must be more closely spaced and locations chosen carefully using a detailed sedimentologic model in these types of compartmentalized reservoirs to increase hydrocarbon recovery.

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Approaches to Characterizing Fluid-Flow Heterogeneity in Carbonate Reservoirs

By Christopher J. Schenk[1]

INTRODUCTION

This report reviews recent research on approaches to characterize fluid-flow heterogeneity within carbonate reservoirs. Fluid-flow heterogeneity is defined as the inability of a rock matrix to allow fluid to flow evenly in all directions because the connections between pores is unevenly distributed. As a reservoir characteristic, carbonates exhibit extreme heterogeneity with respect to fluid flow (Jardine and others, 1977; Jardine and Wilshart, 1987; Kittridge and others, 1990; Wardlaw, 1990a). When attempting to produce hydrocarbons from these reservoirs during any stage of recovery (primary, secondary, or tertiary), fluid-flow heterogeneity dictates production strategy and economics.

Carbonate reservoirs consist of a diversity of particle types, sizes, and compositions that are highly susceptible to interparticle and intraparticle diagenesis, including dolomitization, cementation, dissolution (including vugs and karstification; Kerans, 1989), recrystallization, and fracturing. Spatial variations in depositional and diagenetic textures and fabrics, or the alteration of original porosity within carbonate reservoirs create fluid-flow heterogeneity. In this respect, carbonate reservoirs differ from siliciclastic reservoirs, in that interparticle diagenesis dominates the evolution of porosity (Houseknecht, 1987; Jardine and Wilshart, 1987).

HETEROGENEITY EVOLUTION

Fluid capacity and fluid-flow potential in reservoir rocks are generally stated in terms of porosity and permeability, respectively. For carbonate reservoirs, detailed descriptions of porosity have evolved (Choquette and Pray, 1970; Wardlaw, 1979; Lucia, 1983), based on visual, petrographic, and scanning electron microscope examination. Carbonate porosity is complex and difficult to relate to permeability (Lucia, 1983; Lucia and Fogg, 1990). Because carbonate particle type, size, and composition are related to depositional environment (Moore, 1979), most studies of carbonate reservoir rocks begin with defining and describing sedimentary facies, frequently in great detail (Bebout and others, 1987; Moshier and others, 1988). Many studies have demonstrated a relation between facies and ranges of porosity (Keith and Pittman, 1983; Wiggins and Harris, 1984; Jardine and Wilshart, 1987; Dawson, 1988).

However, the modification of depositional (original) porosity through diagenesis makes anything but a general porosity prediction difficult in carbonate reservoirs (Schmoker and Halley, 1982), and reservoir-scale porosity is impossible to accurately predict. Overprinting of depositional fabrics by dolomitization is common, and for many reservoirs dolomitization is critical for generating effective porosity. The uniformity of pore geometry created by dolomitization means the difference between reservoir and nonreservoir facies in many carbonate rock units (Wardlaw, 1979, 1990a; Bliefnick and Mariotti, 1988).

Permeability is less related to facies than to porosity, because diagenetic alterations cause great spatial variability in pore geometry. Thomeer (1983) showed that, for a given porosity, carbonates can exhibit any permeability because of possible combinations of pore-throat size distributions resulting largely from diagenetic variations. This is the reason many porosity-permeability cross-plots exhibit a "shotgun blast" pattern.

However, if pore-throat sizes exhibit a narrow range of sizes, then permeability shows a better correlation to porosity. Lucia (1983) demonstrated that permeability in a given carbonate reservoir can be correlated to certain types of porosity, not total porosity. Visual descriptions of porosity, especially the recognition of vugs, are essential in the process of attempting to correlate porosity with permeability. Bebout and others (1987) documented a relation between mean permeability and carbonate facies within the Permian Grayburg Formation in the Permian basin, but the range of permeability within each facies meant that permeability predictions based on mean values were impossible at a local scale.

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MEASURING HETEROGENEITY

Scanning electron microscope analysis of pores and pore casts has been used to determine the size distribution of pores (Wardlaw, 1976, 1990b; Wardlaw and Li, 1987). In general, the lower the ratio of pore size to pore-throat size, the higher the porosity and permeability (Wardlaw, 1976, 1979) and the better the reservoir quality. Groupings of pore-throat sizes in carbonate reservoirs have been related to ranges of porosity and permeability (Lindsay, 1988), and this approach may be useful in providing a predictive capability for ranges of porosity and permeability for a given reservoir. These ranges may or may not follow facies boundaries, but may define reservoir flow units, which is the first step in defining fluid flow patterns and unraveling heterogeneity in reservoirs (Major and Holtz, 1990).

A common approach to understanding fluid-flow heterogeneity in carbonate reservoirs is to measure pore-throat size from mercury injection-capillary analyses (Keith and Pittman, 1983; Wiggins and Harris, 1984; Kent and others, 1988). This technique provides data that allow the calculation of size distributions of pore throats. The attractiveness of this approach is that the pore-throat size distribution integrates the effects of complex diagenetic alterations, including dolomitization, into a measurable quantity. Combining mercury injection-capillary pressure analyses with petrographic image analyses of pore geometries is a powerful method to quantify both the types of pores and the distribution of pores within a reservoir rock (Etris and others, 1988). Reservoir rocks with similar pore geometries may have similar permeabilities, and thus this technique may help to define flow units.

Mercury injection-capillary pressure data will provide information on the pore geometry of the rock matrix, including the contribution of vugs to porosity, but in many carbonate reservoirs the flow paths and permeability depend on fractures. Fractures can be simple to extremely complex (Ijirigho, 1981), and fractures commonly are missed when samples are prepared for injection analyses. The contribution of fractures and brecciation to the permeability network of any carbonate rock must be carefully considered when defining flow units.

INTRAWELL HETEROGENEITY STUDIES

Intrawell studies demonstrate an approach that characterizes heterogeneity in carbonate reservoirs using pore-throat and pore sizes to define flow units. Subsurface information available to the investigator include core and log data.

Keith and Pittman (1983) used mercury injection curves to define sizes of pore throats in the Lower Cretaceous Rodessa Limestone, Running Duke field, East Texas basin. Pore-throat size and distribution were related to facies; skeletal limestone had a unimodal size distribution of pore-throat radii, whereas ooid limestone had a bimodal size distribution of pore-throat radii. Because micropores hold bound water in one part of the bimodal pore network, the ooid facies produced water-free gas compared to production from the unimodal-sized skeletal facies. They developed borehole log-based cross-plot techniques for identifying these types of pore systems throughout the field where core data were not available, and for allowing this type of heterogeneity to be traced throughout the field.

Wiggins and Harris (1984), in a study of the Lower Cretaceous Pettit Limestone in the East Texas basin, recognized four major pore types and their associated pore-throat sizes. They related specific diagenetic alterations to each class of pore-throat size. Pore-throat size was the parameter that limited fluid access between pores and thus was a critical measurement for determining possible patterns of fluid flow. In addition, the examination of pore-throat sizes provided a perspective from which the importance of specific diagenetic effects on fluid flow in the reservoir were assessed. Wiggins and Harris (1984) found that reservoir quality depended on the proportions of blocky calcite spar cement to microspar cement because these cements controlled the sizes of pore throats.

In a study of grainstone reservoirs of the Upper Jurassic Smackover Formation, Mississippi and Alabama, Bliefnick and Mariotti (1988) documented a correlation between increasingly dolomitized rock and improved reservoir quality. Pore-throat sizes determined from mercury injection became larger with increasing degree of dolomitization, as did the size of dolomite crystals. They concluded that fluid-flow heterogeneity in the Smackover Formation was a product of extreme lateral facies variability and irregular dolomitization.

Kent and others (1988) described pore systems from 10 carbonate reservoirs in Mississippian rocks of the northern Williston basin. They documented the degree of size uniformity of pore-throat radii in each reservoir, and they related families of pore-throat sizes to individual or combinations of porosity types. They found that dolomitization produced a rather uniform pore-throat size distribution, and so dolomites made better reservoirs. They also found that carbonate reservoirs with similar porosities can exhibit vastly different pore-throat size distributions, again demonstrating that porosity correlations do not necessarily lead to flow-unit definition.

Lindsay (1988) related ranges of pore-throat radii to ranges of porosity and permeability in Mississippian carbonate reservoirs of the Mission Canyon Formation, North Dakota. He developed a model of four pore types and two pore-throat sizes for the Mission Canyon, and concluded that understanding heterogeneity meant knowing (1) all sizes of pore throats and pores, (2) how pores are connected, and (3) how fluids with different viscosities move through the pore system. Combinations of the four types of pores and pore throats create complex pore systems.

Inden and others (1988) found that porosity alone did not differentiate reservoir from nonreservoir carbonate rock in the upper part of the Interlake Formation (Upper Ordovician and Silurian) in the Nesson anticline area, Williston basin. They found that the variability in morphology of pore connections, pore sizes, and pore distributions caused differences in permeability that had to be carefully examined, along with water saturations, to determine the spatial distribution of flow units.

INTERWELL HETEROGENEITY STUDIES

The intrawell studies demonstrate an approach that characterizes heterogeneity in carbonate reservoirs using pore-throat and pore sizes to define flow units. The principal difficulty is to make the step from core or log data to interwell correlations of flow units defined from studies of pore systems in several wells.

Jardine and Wilshart (1987) studied fluid-flow heterogeneity of several Devonian carbonate reservoirs in the western Canada basin for the purpose of observing the progress of enhanced recovery techniques. Their reservoir analysis of reef carbonate of Judy field is particularly instructive. They grouped several carbonate facies into three classes of porosity and permeability to define three major flow units in reefal carbonate reservoirs. Borehole logs from 47 wells were used to construct cross sections depicting the three-dimensional configuration of the flow units in the field. The interlayering and juxtapositioning of the three flow units with relatively impermeable rock resulted in an extremely heterogeneous reservoir with respect to fluid flow. This study is an excellent example of an attempt to determine the interwell correlation of flow units and the degree of three-dimensional fluid-flow heterogeneity in a carbonate reservoir.

Lucia and Fogg (1990) used geostatistical techniques to determine the scale over which core permeabilities were valid in the Permian Grayburg Formation, Dune field, west Texas. Using a combination of core analysis, rock fabric, and log data, statistical techniques were used to determine interwell correlation of permeable carbonate units. Statistical techniques indicated a possible correlation of permeability values over vertical length scales of 4 to 5 feet and 12 to 13 feet, and a correlation of permeability values over horizontal length scales of 2,000 and 1,000 feet (parallel and perpendicular to the main grainstone trend, respectively).

Another approach to understanding carbonate fluid-flow heterogeneity is to directly measure the three-dimensional distribution of permeability and determine the statistical correlation lengths of permeability in a grid placed on an outcrop. This approach focuses on determining the statistical length scales over which measured permeabilities are valid in the reservoir being investigated.

Kittridge and others (1990), in a study of dolomite reservoir facies of the Lower Permian San Andres Formation, Permian basin, west Texas, compared vertical and horizontal permeabilities from outcrop and subsurface samples. They reported over four orders of magnitude variation in permeability, in bed-to-bed measurements and also within beds. The scale of spatial correlation of permeability varied with the spacing of measurements. They reported a correlation length of 3 to 5 feet for permeabilities measured 0.5 feet apart and a correlation length of 0.25 feet for measurements taken 1 to 0.5 inch apart. Given typical oil-field well spacings, these length scales suggest that interwell correlation of permeable units will be difficult. Although few of these types of studies have been completed, the value of using outcrops of carbonates to understand three-dimensional heterogeneity has been demonstrated (Waters and others, 1989).

SUMMARY

Permeability variations in carbonates are controlled by variations in pore geometry, thus measuring the pore geometry directly is an attractive approach to begin to understand fluid-flow heterogeneity. Flow units defined from data on the geometry and distribution of pore systems, along with facies, porosity, permeability, and fracture data, may possibly be correlated well to well using stratigraphic or statistical techniques.

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Mineral Transformations in Tar Sand and Heavy Oil Reservoirs Induced by Thermal Recovery Methods

By Christopher J. Schenk[1]

INTRODUCTION

This paper reviews research on mineral transformations that occur when heavy oil and tar are produced from sand reservoirs using thermal recovery methods. Tar sands, more appropriately termed natural asphalts (Meyer and deWitt, 1990), exhibit viscosities greater than 10,000 centipoises (cP). Heavy and extra heavy oils have viscosities less than 10,000 cP, and also generally have API gravities of 10 to 20 degrees and less than 10 degrees API, respectively (Cornelius, 1987). Viscosities of this order dictate that some method must be used that will reduce the viscosity so that the hydrocarbons can be mobilized and recovered. The most common method used is heating (thermal recovery), but chemical recovery methods are also beginning to be used. In situ thermal recovery technology is of two major types; steam injection and combustion. In either process, heat is transferred to the hydrocarbons to decrease viscosity and provide mobility.

Steam Injection

Steam injection is accomplished by one of two main processes: cyclic steaming or continuous injection. In cyclic steaming (also called steam soak or huff-and-puff), steam is injected into a pay zone, then the well is shut-in for a period of time, commonly 40 to 90 days, after which the hydrocarbons are recovered from the same well until recovery becomes uneconomic. The process is then repeated. In continuous steaming, steam is continuously injected into one well, and other wells in the pattern serve as recovery wells.

Conditions of steaming vary, but steam is generally introduced at temperatures ranging from 300°C to 350°C, and at pressures as high as 14 megapascals (MPa). The ratio of water to rock is high during the steaming process, and is relatively lower during combustion. Recoveries of heavy oil or natural asphalt from the steam process rarely exceed 20 to 25 percent of the original oil-in-place (OOIP) (Carrigy, 1983), although recoveries of 60 percent have been noted from small zones in core (Hutcheon, 1984).

In Situ Combustion

In situ combustion is achieved by pumping air or oxygen down a well into a pay zone, and igniting the hydrocarbons by electrical or other means (Moore and others, 1989). The burning hydrocarbon front creates a zone of mobile oil that is then produced. Conditions of combustion are complex (Hutcheon, 1984); temperatures can reach 800°C in the immediate zone of combustion, but decrease rapidly away from the zone. Pressures are generally less than 20 MPa. The water-to-rock ratio is extremely low compared to steam injection, in part because combustion vaporizes formation water. Exceptions to this are combustion projects combined with waterflooding ("wet combustion"). Recoveries from pilot combustion tests vary, but recoveries as high as 67 percent of the OOIP (for natural asphalt deposits) have been reported (Carrigy, 1983).

Mineral Transformations Studies

Maximum temperatures associated with thermal recovery processes (300–350°C for steaming, 800°C for combustion) enhance chemical reactions between the reservoir rock, formation fluids, and injected fluids (Hutcheon, 1984). Important factors to consider in terms of diagenesis produced by thermal recovery ("artificial diagenesis" of Hutcheon, 1984) include changes in detrital framework mineralogy, authigenic mineralogy, distribution of authigenic minerals in a pore system, temperature distribution, length of exposure to maximum temperature, pore-fluid chemistry, injected fluid chemistry, the water-to-rock ratio, and the timing of diagenesis relative to permeability loss and hydrocarbon mobiliza-

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tion. Only a few of these factors are known in detail for thermal recovery processes. Studies of artificial diagenesis are based on either (1) closely spaced cores taken before and after pilot tests of thermal recovery processes or (2) experimental steaming or burning of samples taken from field cores.

STEAM INJECTION—FIELD STUDIES

A detailed examination of cores from the Cretaceous Clearwater Formation in the Cold Lake area, Alberta, before and after 2 years of continuous steamflooding (maximum of 260°C for 1 year) was conducted by the Sedimentology Research Group (1981). The pre-steam pay sandstones were dominantly feldspathic litharenites, with chert, volcanic rock fragments, and shale composing the lithic fraction. Less than 10 percent matrix was present. Pre-steam diagenesis was complex, and included quartz and feldspar overgrowths, minor zeolites, calcite and dolomite cements, kaolinite, illite, chlorite, and minor smectite.

Post-steam analysis illustrated that most of the illite, chlorite, and kaolinite was removed, whereas coarse smectite coatings (4 to 20 μm) and analcime formed in the pore system. Dissolution of the surfaces of detrital quartz, feldspar, and lithic grains was observed. Chert recrystallized to a coarser texture. The main chemical change appeared to be kaolinite plus quartz plus feldspar went to coarse smectite. Smectite growth and possibly some compaction associated with oil removal from these shallow reservoirs resulted in a 25 percent loss of porosity. The formation of pore-bridging smectite and the migration of clays and zeolites served to block pore throats, reducing visual permeability relative to pre-steam samples.

Lefebvre and Hutcheon (1986) examined pre- and post-steamflood cores from a heavy oil reservoir in the Lower Cretaceous Sparky Formation, Lloydminster area, Saskatchewan. Pre-flood mineralogic analysis showed the sandstones to be dominantly quartz arenites, with less than 5 percent feldspar and lithic grains. Diagenetic minerals included quartz and feldspar overgrowths, kaolinite, siderite, and ankerite.

Post-steam analysis indicated that illite and chlorite formed at the expense of kaolinite, detrital quartz, and feldspar. Chlorite may have formed from a reaction between siderite and kaolinite. Illite occurred as a replacement of potassium feldspar, and also as thin linings in pores and on kaolinite. However, these post-steam mineralogic changes are minor when compared to the changes observed in lithic sands of the Clearwater Formation.

A similar comparison was made of pre- and post-steamflood mineralogic changes between quartz arenites of the Clearwater Formation from the Cold Lake area and lithic arenites of the Sparky Formation from the Lloydminster area (Hutcheon and others, 1989b). The extent of artificial diagenesis was less in quartz arenites than lithic arenites. As in previous studies, Hutcheon and others (1989b) found that smectite and analcime formed in the lithic arenites, whereas only minor diagenesis occurred in the quartz arenites.

An important aspect of Hutcheon and others (1989b) is the documentation that the chemistry of produced waters reflects chemical reactions occurring in the reservoir during steaming, and that modeling of the water chemistry can be used qualitatively to predict chemical reactions. This use of water chemistry is an active area of research (Gunter and others, 1989; Russell and Bird, 1989; Hallam and others, 1990).

CO_2 was documented as an important by-product of carbonate mineral dissolution during steaming in both formations. Cathles and others (1990) also documented the release of CO_2 from carbonate minerals during steaming. Hutcheon and others (1990) suggest that reactions involving natural asphalt, in addition to carbonate dissolution, may produce CO_2 during steam stimulation.

STEAM INJECTION—EXPERIMENTAL STUDIES

To understand the effect of steaming on reservoir mineralogy, many studies have experimentally steamed core in laboratory autoclaves. In an excellent early study of experimental steaming, Day and others (1967) steamed core recovered from 10 different reservoirs within the United States and documented all mineralogic changes. The most critical mineralogic change related to steaming that occurred in nearly all reservoirs was the formation of smectite at the expense of dolomite and kaolinite. Smectite that forms in a reservoir pore system can adversely affect permeability.

Boon and Hitchon (1983a, b) experimented with tar sands from the Lower Cretaceous McMurray Formation in the Athabasca deposit, Alberta, Canada. They concluded that a major reaction in these deposits was illite plus kaolinite plus quartz converted to smectite. They also documented the dissolution of quartz and the formation of colloids. Colloids such as these produced experimentally might be missed in field studies of artificial diagenesis because of sampling problems.

Boon and others (1983) steamed cores of lithic sandstones of the Clearwater Formation from the Cold Lake area of Alberta, which was the same reservoir rock studied in field cores by the Sedimentology Research Group (1981) and Hutcheon and others (1989a,b). Boon and others (1983) observed the dissolution of quartz, dolomite, and kaolinite and the formation of smectite, chlorite, and calcite. Smectite and chlorite grew as pore linings and bridges that were interpreted to cause the reduction in permeabilities from pre-steam values. Reactions were controlled by pH, temperature, and salinity. All experiments demonstrated the translocation of "fines" (probably clays) through the pore system, clogging pore throats and "significantly reducing" permeability. They suggested that all mineral reactions may not have a negative effect on hydrocarbon recovery; some reactions may result in a reduction of permeability in steam thief zones, decreasing steam losses and improving recovery.

Bird and others (1986) experimented with what appear to be quartz arenites from the Lower Cretaceous McMurray Formation in the Athabasca area, Alberta, to document the process of quartz dissolution. Upon cooling, solutions charged with excess silica from quartz dissolution led to the formation of quartz cements, amorphous silica, and minerals including zeolites and smectite. High silica concentrations can also produce complex silica colloids during steaming (Potter and Dibble, 1983). Colloids can be disastrous to thermal recovery operations, as they can plug pumps, piping, and other equipment, but colloids may also be beneficial in plugging highly permeable steam thief zones. Colloids have been reported from nearly all experimental thermal studies (Boon and Hitchon, 1983a,b; Bird and others, 1986), and they should be expected to occur in field situations.

Kirk and others (1987) steamed lithic sandstones of the Clearwater Formation from the Cold Lake area, Alberta. Pre-steam mineralogy included minor smectite, illite, kaolinite, zeolites, feldspar overgrowths, and pyrite. Post-steam analysis indicated that quartz, dolomite, and kaolinite dissolved, CO_2 was produced, smectite content doubled, and calcite cement formed. Post-steam fluids were supersaturated with respect to silica. Smectite was deposited as thick rims around framework grains, and was the cause of permeability reduction from 50 to 98 percent of pre-steam permeability values. They concluded that (1) solution pH and temperature were the most important variables controlling diagenesis, and (2) solution kinetics were more rapid than expected.

Gunter and Bird (1988) steamed chert-bearing sublithic arenites from the Cretaceous Grand Rapids Formation from the Cold Lake area, Alberta. Pre-steam authigenic minerals included kaolinite, calcite, minor illite, and smectite. Post-steam analysis showed that calcite was totally removed, much of the kaolinite and illite was removed, and some dissolution of quartz occurred. The smectite content increased by 35 percent. The main reaction appeared to be calcite plus quartz plus kaolinite converted to Ca-smectite plus CO_2. They noted that solution kinetics, especially the dissolution of calcite and the release of CO_2, were extremely rapid.

This and other studies of artificial diagenesis have noted the production of CO_2 during steam injection. CO_2 appeared to be a product mainly of carbonate mineral dissolution. CO_2 may actually improve recovery during thermal stimulation by (1) further reducing hydrocarbon viscosity and (2) by causing swelling of the oil (by included gas) that results in higher oil saturations and increased recovery of the OOIP.

Monin and Audibert (1988) heated heavy crude oil to 350°C in the presence of reservoir minerals to observe changes in the character of the oil. An important and detrimental by-product of heating was the rapid formation and deposition of insoluble organics (pyrobitumen). These experiments simulated steam conditions, and suggested that pyrobitumen could form rapidly as the oil was heated, possibly plugging permeability in a reservoir undergoing steam stimulation.

Bizon and others (1984) experimentally steamed natural-asphalt-bearing carbonate rock from the Devonian Grosmont Formation of Alberta. Pre-steam mineralogy showed the samples to be 98 percent dolomite, the remainder being quartz, feldspar, diopside, kaolinite, smectite, and pyrite. Post-steam analysis showed dissolution of dolomite, quartz, diopside, feldspars, and possibly kaolinite. Calcite formed, as did amorphous Mg-Ca-Al silicates.

In an extension of this study, Kubacki and others (1984) experimentally steamed carbonate rock of the Grosmont Formation with an initial mineralogy of 98 percent dolomite, 1 percent quartz, and 1 percent illite and kaolinite. They reported the formation of calcite, amorphous Mg- and Mg-Al silicates, hydromagnesite, margarite, huntite, and amorphous Fe compounds. They also reported having trouble measuring permeability, but concluded that overall permeability had decreased during the experiments largely because of translocation of fines in the pore system.

Hutcheon and Oldershaw (1985) experimentally flooded carbonate rock of the Grosmont Formation with solutions at 180°C. Pre-steam mineralogy of the carbonate rock was mainly dolomite, but included calcite, quartz, feldspar, illite, and kaolinite. Post-flood analyses indicated that smectite formed at the expense of dolomite and kaolinite. The formation of amorphous silicates as in the previous studies of carbonates was not reported. Authigenic smectite constituted less than 1 percent of the total rock mass, but smectite reduced permeability as much as 25 percent of pre-steam values, whereas porosity increased slightly. Although carbonate rocks do not appear to be as affected by steaming as siliclastic rocks, an increase in smectite content of about 1 percent was enough to significantly impede the permeability in the complex pore system of the carbonate rock.

COMBUSTION—FIELD STUDIES

Many field pilot tests of in situ combustion have been made in the last 30 years (Moore and others, 1989), but few studies have documented the details of mineralogic changes induced by combustion. Lefebvre and Hutcheon (1986) examined quartz arenites from the Lower Cretaceous Sparky Formation in the Lloydminster heavy oil deposit, Saskatchewan, Canada, before and after combustion. Pre-fireflood mineralogy included quartz, feldspar, kaolinite, siderite, and ankerite. Post-fireflood analysis indicated combustion temperatures had reached somewhat higher than 540°C. Illite, chlorite, and minor potassium feldspar and hematite formed in the burned zone, and kaolinite was removed. In general, fireflooding did not have much of an effect on the mineralogy of the sandstones, in part due to the lack of an aqueous phase compared to steamflooding. No smectite formed, and only a minor reduction in porosity was reported. However, Hutcheon (1984) noted that reservoir heterogeneity had a strong effect on the efficiency of fireflood sweep.

COMBUSTION—EXPERIMENTAL STUDIES

Perry and Gillott (1979) formed smectite in a simulated wet combustion process using mixtures of quartz, kaolinite, and dolomite. In the actual combustion zone, where much less water was present than in the surrounding zones, they documented the decomposition of kaolinite at 500°C to 550°C and the decomposition of smectite at about 650°C. They used lithic sandstones from the Cretaceous Clearwater Formation of the Cold Lake area, Alberta. Perry and Gillott (1982) expanded their firetube experiments to include other minerals, and determined the temperatures at which common minerals such as dolomite, kaolinite, illite, chlorite, and smectite decomposed in a combustion zone. Although this study has been criticized because the sandstones were disaggregated and repacked before ignition (Hutcheon, 1984), it is one of the few laboratory studies that reports the effects of combustion on mineralogy. Hutcheon (1984) concluded that porosity may actually increase during combustion, and that overall much less permeability-reducing diagenesis occurs with dry combustion than with steam injection.

Moore and others (1989) summarized the state of the art of combustion technology, and cited over 220 firetube experiments using rock from 46 different reservoirs. However, these experiments were run primarily to investigate the operational aspects of fireflooding, such as temperature distribution, timing of burn, and the mobilization of hydrocarbons. Details of mineralogic changes are not provided. This is true of reservoir studies within the United States, where early firetube experiments were directed toward understanding fireflood technology rather than mineralogic changes (Burger and Sahuquet, 1973).

SUMMARY

More artificial diagenesis occurs during steam injection compared to combustion, probably because more water is present during steaming. However, more studies of the effects of combustion on mineralogy are needed and, in particular, studies on mineralogic changes that occur during wet combustion. In general, the more complex the pre-thermal mineralogy, the more artificial diagenesis can be expected in the reservoir rock. This review shows that few generalizations can be made in terms of specific mineralogic changes during thermal stimulation, except that smectite is commonly formed at the expense of dolomite, kaolinite, and illite. Carbonate reservoirs containing viscous hydrocarbons appear to be less damaged by thermal stimulation than siliciclastic reservoirs, but even minute growth of smectite significantly reduces permeability in carbonate pore systems.

More information is needed on the timing of artificial diagenesis, its effect on porosity and permeability, and the timing of hydrocarbon mobilization. Although many studies have documented permeability reduction related to the growth of smectite or colloids, the unknown factor is the timing of the growth of these phases relative to oil mobilization. If they form after oil is mobilized and recovered, then most artificial diagenesis is not detrimental. If they form before or during oil mobilization, then any permeability reduction greatly affects recovery. The relatively low recoveries associated with steaming compared to combustion is a signal that diagenesis does have an effect on recovery.

In a study of cores from a conventional reservoir that bears on this problem, Sayegh and others (1990) experimentally flooded sandstones with CO_2-bearing water, and found that permeability decreased rapidly as fines were mobilized with high flow rates (similar to steaming), and partially plugged pore throats. However, as the experiment proceeded, permeability increased to about 75 percent of initial values as carbonate minerals were dissolved. This study illustrated the dynamics of the chemical and flow system, and this type of experimentation needs to be done using cores containing heavy oil or natural asphalt to determine timing of oil mobilization relative to permeability changes.

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Biomarkers as Thermal Maturity Indicators

By Paul G. Lillis[1]

Biological markers (biomarkers) are organic compounds in sedimentary rocks and petroleum that can be linked to biological precursor molecules derived from living organisms (Eglinton and Calvin, 1967; Speers and Whitehead, 1969). Biomarkers in rock extracts, pyrolysates, and petroleum are measured by gas chromatography-mass spectrometry, usually expressed as the relative abundance or ratios of specific biomarker compounds. Biomarkers are essentially molecular fossils and have been used as indicators of paleoecology, depositional environment, and paleogeography (Huang and Meinschein, 1979; Didyk and others, 1978; Brassell and others, 1983; Brassell and others, 1987; see Clayton, 1989, for a brief literature review).

Biomarkers rarely retain their original chemical structure because of diagenetic alterations in the water column and shallow sediments and the effects of temperature with deeper burial. Consequently, it is often difficult to correlate a biomarker found in the geosphere with a specific source organism. However, in some cases the biomarker reaction pathway from the biological form through several diagenetic steps to the most stable form has been studied in great detail (such as steroids; see de Leeuw and Baas, 1986, for details).

Early studies revealed systematic changes in biomarker composition with increasing depth of burial (Philippi, 1965; Ensminger and others, 1974). Certain biomarker ratios were compared with the thermal maturation of organic matter, that is, changes in coal rank, vitrinite reflectance, or the generation of petroleum (Didyk and others, 1975; Mackenzie and others, 1980; Mackenzie and Maxwell, 1981; Radke and others, 1980), and consequently have been utilized as thermal maturity indicators for petroleum and source rocks in sedimentary basins.

Biomarker ratios that systematically change with increasing burial (temperature and time) are a function of one or more geochemical reactions. In some cases a biomarker ratio has been attributed to a specific reaction (Mackenzie and McKenzie, 1983) (table 5) while most ratios are probably influenced by several reactions occurring simultaneously or in series. The rate of the specific or overall reaction is assumed to follow first-order kinetics, so the Arrhenius equation may be applied (Mackenzie and McKenzie, 1983; Alexander and others, 1986). The Arrhenius equation can be expressed as:

$$k' = A \exp(-E/RT) \qquad (1)$$

where:

k' = rate constant,
A = frequency factor (1/s),
E = activation energy (kJ/mol),
R = gas constant, and
T = temperature (K).

The extent of a reaction as expressed by a biomarker ratio (table 5) is proportional to $\exp(-k't)$ where t is elapsed time and k' is a function of temperature (equation 1). When the kinetic constants (A and E) are determined for the reaction, then the biomarker ratio may be used to help define the thermal history of sedimentary rocks (Beaumont and others, 1985; Hong and others, 1986; Mackenzie and others, 1988; Chiaramonte and others, 1988). The thermal history may in turn be applied to quantitative models for petroleum generation and migration (Tissot and others, 1987; Suzuki, 1990).

Several approaches have been utilized to determine the kinetic constants (A and E) using natural samples or laboratory experiments. Data from natural samples (downhole trend) may be used assuming a known sediment burial and thermal history, no significant facies variation downhole, and no sample contamination from migrated hydrocarbons. In determining the kinetic constants from a downhole trend, Mackenzie and McKenzie (1983) used an isothermal time-step model whereas Alexander and others (1986) used a linear heating rate function. On the other hand, Lewan and others (1986) and Rullkötter and Marzi (1988) derived the kinetic constants from a series of isothermal hydrous pyrolysis experiments which have the advantages of no facies variation (using replicate samples) and precisely known time and temperature conditions. However, hydrous pyrolysis conditions (high temperature, short time, closed system) differ from natural conditions, and the derived kinetics may not be applicable. Marzi and others (1990)

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Table 5. Selected maturity ratios based on an apparent biomarker reaction (from Mackenzie, 1984)

Apparent reaction	Ratio	End value
Isomerization of C17α,21β(H) homohopanes at C-22 chiral center ---------------	$\frac{22S}{22S+22R}$	0.6
Isomerization of 5α(H)14α(H)17α(H) C_{29}sterane at C-20 chiral center ---------	$\frac{20S}{20S+20R}$	0.54
Aromatization of C-ring monoaromatic sterane to triaromatic steroid-------------	$\frac{\text{Triaromatic}}{\text{Tri- + Monoaromatic}}$	1.0
C-C bond cleavage of C_{28} triaromatic steroid to C_{20} triaromatic steroid[a] -------	$\frac{C_{20}\text{ triaromatic}}{(C_{20}+C_{28})\text{ tri-}}$	1.0

[a]Mackenzie (1984) stated that apparent carbon cleavage reaction may actually be a reflection of higher stability of the C_{20} triaromatic steroid.

suggested that more precise kinetic parameters may be derived from combining natural data with experimental data.

Specific biomarker reactions are far from the ideal thermal maturity indicator (see Curiale and others, 1989 for discussion) because they generally have a narrow dynamic range of maturity, and many reach the endpoint or equilibrium point before the main stage of petroleum generation (Mackenzie, 1984). Also, biomarker concentrations decrease significantly at higher maturity (eventually reaching the instrument detection limits), which increases the chance of contamination or alteration effects. Because biomarker reactions are typically measured as the relative abundance or ratio of the reactant and the product, the actual concentrations are not known. Therefore an apparent transformation may actually be one compound being destroyed at a faster rate than the other (Requejo, 1989) or be the combined effects of release reactions from a "bound" state and destruction reactions (Abbott and others, 1990). Competing reactions may be the cause of observed reversals in some biomarker maturity trends (Lewan and others, 1986; Strachan and others, 1989; Peters and others, 1990).

Biomarker ratios need not be representative of a specific reaction to be useful as thermal maturity indicators. For example, Alexander and others (1986) defined some aromatic maturity indicators by determining the kinetics of the overall pseudo-reactions. Biomarker ratios that change systematically with burial may be used on a relative maturity basis or may be empirically calibrated with vitrinite reflectance (Radke and Welte, 1983) or a maturity indèx (van Grass, 1990). However, empirical calibrations are influenced by variations in stratigraphy, thermal history, and biomarker reaction kinetics; and the maturity parameter should be applied with caution to other areas. Changes in vitrinite reflectance are controlled by a complex series of reactions with the resulting large dynamic range in maturity (Burnham and Sweeney, 1989). Separate calibrations for an array of heating rates would be required to correlate the behavior of vitrinite maturation with a biomarker maturity ratio.

Some biomarker ratios are sensitive not only to maturity but to composition of organic matter (Seifert and Moldowan, 1978; ten Haven and others, 1986), to pH or redox potential in the depositional environment (Moldowan and others, 1986), or to rock matrix effects (Lu and others, 1989; Strachan and others, 1989). Although some source and matrix effects are minor, these ratios should be used with caution if the effects cannot be taken into account.

Despite all the above complications, biomarkers are a useful tool for determining the thermal maturity of oils and source rocks, and research continues to refine the technique. One promising area might be to use a distribution of activation energies to model a biomarker maturity parameter that describes a diversity of reactions (Burnham, 1989) analogous to some kinetic models applied to petroleum generation. For a more extensive discussion on the application of biomarkers as thermal maturity indicators, refer to Curiale and others (1989) and Mackenzie (1984).

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Fission-Track Analysis in Sedimentary Basins—1992

By Nancy D. Naeser[1]

INTRODUCTION

Fission tracks in apatite and zircon have been used in a wide range of studies in sedimentary basin analysis (reviewed in N.D. Naeser, 1989a; N.D. Naeser and others, 1989b). The annealing of fission tracks and the resulting effect on fission-track age and track lengths, particularly in apatite, have been used to reconstruct the thermal history of basins from the deposition and burial of sediments through subsequent cooling related to uplift and erosion. Annealing is also used to constrain localized temperature anomalies, such as those related to intrusions and to the passage of high-temperature fluids through a basin. Fission-track analysis of detrital zircons helps set limits on maximum paleotemperatures in basins and determine the provenance of sediments (C.W. Naeser, 1979b; Gleadow and others, 1983, 1986a, 1986b; N.D. Naeser and others, 1987b, 1989b; Green and others, 1989a; Hurford and Carter, 1991). Fission-track analysis is useful in sedimentary basin studies because it provides both *temperature* and *time* information over a temperature range that coincides with hydrocarbon generation (Gleadow and others, 1983; N.D. Naeser and others, 1989b) and burial diagenetic processes (for example, clay diagenesis and conodont color alteration) and with paleothermal anomalies associated with some mineral deposits (C.W. Naeser and others, 1980; Cunningham and Barton, 1984; C.W. Naeser and Cunningham, 1984; Beaty and others, 1988).

Apatite fission-track analysis has been used to clarify the thermal history of more than 40 sedimentary basins worldwide, including North America (Briggs and others, 1979, 1981; Dokka, 1982; Lakatos and Miller, 1983; Crowley and others, 1985, 1986; Johnsson, 1985, 1986; Giegengack and others, 1986, 1990; Miller and others, 1986, 1990; N.D. Naeser, 1986, 1989b; Zimmermann, 1986; Duddy and others, 1987; N.D. Naeser and others, 1987a, 1989a, 1989b, 1990a, 1990b; Crowley and Kuhlman, 1988; Dumitru, 1988, 1989; O'Sullivan, 1988; Geving and others, 1989, 1990, 1991; O'Sullivan and others, 1989, 1990; Arne and others, 1990a, 1990b; Kelley and Blackwell, 1990; Kohn and others, 1990b; Kveton, 1990; Roden and others, 1990; Crowley, 1991; Kelley and others, 1991; McMillen and O'Sullivan, in press; among others), Australia (Duddy and Gleadow, 1982, 1985; Gleadow and others, 1983; Gleadow and Duddy, 1984; Marshallsea, 1986; Duddy and others, 1987; Arne and others, 1989, 1990b; Green and others, 1989a; Gleadow, 1990), New Zealand (Green and White, 1985; Seward, 1989; Kamp and Green, 1990), Europe (Green, 1986, 1989a, 1989b; Qvale and others, 1990), and elsewhere (Duddy and others, 1984; Corrigan and Crowley, 1989; Feinstein and others, 1989; Hansen, 1990; Hill, 1990; Kohn and others, 1990a). These studies have produced extensive information on fission tracks and their response to the thermal history of sedimentary rocks and in many areas have provided information on thermal history that would be difficult to obtain otherwise. At the same time, these studies have highlighted several questions that remain to be resolved before the full potential of apatite fission-track analysis in basin studies can be realized.

ANNEALING KINETICS

Although temperature is the dominant controlling factor in annealing, time cannot be ignored in interpreting thermal history. The temperature range for annealing of any given mineral depends on the duration of heating—the shorter the heating, the higher the temperature required for annealing. More research has been devoted to determining the annealing kinetics of apatite than of any other mineral, both by laboratory heating experiments (for example, C.W. Naeser and Faul, 1969; Märk and others, 1973; Zimmermann and Gaines, 1978; Crowley, 1985; Green and others, 1985, 1986, 1989b; Crowley and Cameron, 1987; Laslett and others, 1987; Duddy and others, 1988; Green, 1988; Crowley and others, 1990, 1991; Hughes and others, 1990) and by empirical observations of annealing behavior in drill holes (C.W. Naeser, 1979a, 1981; Gleadow and Duddy, 1981). However, uncertainties still remain. At least nine laboratories are currently involved in research to more accurately de-

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fine the kinetics of apatite annealing and thus improve the practical application of apatite annealing models.

APATITE COMPOSITION

Laboratory studies and observations from drill holes have established that Cl-apatite anneals at temperatures up to about 30°C higher than other common apatite varieties (F-, Sr-F-, and OH-apatite), affecting the variation in both age and track lengths with progressive annealing (Green and others, 1985, 1989a; Crowley and Cameron, 1987; Crowley and others, 1990; Hughes and others, 1990). Fortunately, apatite suites are commonly so dominated by F-apatite with insignificant amounts of chlorine (for example, Berry and Mason, 1959; Deer and others, 1962; N.D. Naeser and others, 1987a) that most samples can be reasonably interpreted using F-apatite annealing data. Composition may pose a problem, however, for interpreting thermal history in basins where the detrital apatites have a wide and variable range in Cl-content. Apatite composition is normally determined by electron microprobe. An ongoing challenge is to develop an alternative, routine method for determining composition (particularly Cl-content) in individual apatite grains that will eliminate the need for electron microprobe analysis (Siddall and Mendelssohn, 1990; C.W. Naeser, oral commun., 1991).

INHERITED AGE AND THERMAL HISTORY OF DETRITAL APATITE

It is obvious that detrital minerals entering a depositional basin carry with them previously formed fission tracks that reflect the thermal history of the sediment source. Furthermore, detrital apatites in sedimentary rocks are typically derived from parent rocks of widely varying age and thermal history. Thus, the observed variations in apatite age and track-length distribution with depth in any given sedimentary basin will reflect the age(s) and thermal history(s) of the parent rocks, as well as the thermal history of the depositional basin and the compositional variability of apatite. These factors, combined with the variation between sedimentary basins in annealing caused by differences in heating histories, must be considered when interpreting apatite fission-track data from sedimentary rocks. Models that assume that variation in age and track lengths is only related to the thermal history of the sedimentary basin, or that all apatites came into the depositional basin with a simple (volcanic) track-length distribution, can produce significant errors in interpreted thermal history, particularly in sedimentary rocks that have not been exposed to temperatures sufficient to totally anneal apatite.

RELATION BETWEEN TRACK LENGTH AND TRACK DENSITY

The relation between the reduction in mean track length and fission-track age (track density) with progressive annealing is unclear. Some workers have determined a 1:1 correlation between reduced density and reduced track length in apatite during the early (low-temperature) stages of annealing (Green, 1988), but some research suggests otherwise (C.W. Naeser and others, 1989). Accurate determination of this relation is critical to the practice of some laboratories of "correcting" apatite fission-track ages based on the extent of track-length reduction (for example, Kamp and Green, 1990).

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Vitrinite and Solid Bitumen Reflectance: Some Correlations and Applications

By Mark J. Pawlewicz *and* J. David King[1]

The rudiments of coal petrography/petrology were established in the late 1800's when microscopy was first used to prove that most coal formed from the remains of terrestrial plants (Stach and others, 1982). From this beginning, coal petrography/petrology advanced through the observation of thin sections of coal, primarily for paleobotanical considerations, to the study of polished coal blocks with oil immersion techniques at about 1925. Improvements in optics and the discovery that vitrinite reflectance increases with increasing coal rank were instrumental in achieving great advances in the knowledge of coal. Equipment improvements were marked by progressions in the application for technological purposes, such as the determination of the coking quality of coal, as well as for academic purposes. The history of the application of reflectance analysis to exploration for oil and gas dates from the work of M. Teichmuller (1958) with her reflectance measurements of fine-grained coaly inclusions in sedimentary rocks.

Determination of vitrinite reflectance (R_m) has advantages and disadvantages in assessing thermal maturity with respect to generation of oil and gas. One advantage is the relative mechanical ease of analysis using prepared slides and pellets of coal and organic material (OM) concentrated from sedimentary rocks. Stach and others (1982) and Bustin and others (1983) presented excellent summaries on the aspects of coal petrology/petrography. Davis (1978) discussed the analytical methods for coal reflectance determination. All three references are recommended as they provide good crossover information for the observation and measurement of dispersed organic material.

Vitrinite reflectance is used as a quick index to evaluate the level of thermal maturation of sedimentary rocks (Sikander and Pittion, 1978). Reflectance is correlative to a specific rank of coal, while R_m of dispersed organic matter (OM) is considered in terms of thermal maturity, or relation to the hydrocarbon (HC) generation window. Generally only the "window" of peak generation is used; 0.6 to 1.2 percent R_m for oil, and 1.2 to 2.0 percent R_m for wet gas; greater than 2.0 percent for dry gas. Dow's (1977) correlation chart places the HC generation range between at 0.5 and 3.2 percent. Of course, this is not always the case. Reflectance values below this threshold would most likely be the result of the type of organic material (Waples, 1985), or some process, yet unexplained, operating on the OM (Graham and Williams, 1985; Price and others, 1986). Higher values can be partially explained by the high bireflectance of vitrinite, where a paucity of OM in rocks of high thermal maturity usually results in a wide histogram and a somewhat indeterminate mean value. More succinctly, Waples (1985) states, "Effective generation of HC requires that the generated products be expelled from the source-rock matrix and migrated to a trap. Timing and efficiency of expulsion depend on a number of factors, including rock physics and organic-geochemical considerations."

Samples processed for their organic material can commonly have several distinct populations of vitrinite. For this reason the selection of vitrinite for reflectance measurement is possibly the most error-prone and inconsistent factor in thermal maturity determinations; problems and criteria related to this selection are discussed by Dembicki (1984), Barker and Pawlewicz (1986), Toxopeus (1983), and Powell and others (1982). Walker (1982) and Walker and others (1983) found anomalously low reflectance values, 0.2 to 0.3 percent R_m, in an offshore California HC producing sequence. Price and Barker (1985) provided much insight into these unexpected low R_m values. Local variations in OM type (see Tissot and Welte, 1984, for discussion of kerogen types and relation to HC generation), chemistry of the OM, and other factors determine the values for the "oil window" and affect the probability of any generation having taken place.

A disadvantage of vitrinite reflectance is the lack of precision in predicting thermal maturity at the low end of the reflectance scale, between 0.2 and 0.45 percent R_m. Stach and others (1982) illustrated this in chart form as it applies to coal at the lignite and subbitumi-

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nous levels. Low rank coals are sensitive to the physical environment, such that an increase in the moisture content alone can cause variations in reflectance of 0.1-0.15 percent R_m. This is an important consideration because, due to ease of preparation, coal is the preferred material when working with borehole profiles. This problem is mitigated because the real interest lies at a higher reflectance level. Concentrated OM may or may not be as sensitive to changes in moisture content, but a certain awareness of this problem should be part of any maturity determination done on low rank material.

An advantage of the technique is the direct correlation of reflectance to maximum temperature (Barker and Pawlewicz, 1986). R_m analysis of samples from borehole profiles is used to establish reflectance gradients. The gradients are then used to recognize the upper and lower thermal maturity boundaries of the oil/gas window. Knowing the upper and lower boundaries of the oil window could be used to determine the volume of the source rocks, useful for determining HC resources.

Burial history reconstruction is widely used to illustrate the geologic history of various stratigraphic units. Related to this reconstruction is the use of thermal maturation profiles to estimate the amount of erosion, both at the top and within a sequence. This exercise is predicated on the belief that the reflectance value for vitrinite at the Earth's surface before burial is 0.2 percent. By extrapolating a regression line through a plot of depth versus vitrinite reflectance to the 0.2 percent R_m intercept, the amount eroded is the difference between ground level and the intercept point (Dow, 1977). This simple exercise is complicated by the lack of an accepted surface baseline value. For example, Katz and others (1988) use 0.25 percent R_m in their examples, whereas Vellutini and Bustin (1990) use 0.15 percent R_m.

Burial history reconstruction of Paleozoic basins, which have cooled from their maximum temperatures, presents another problem. Vitrinite reflectance records the maximum temperature (Barker and Pawlewicz, 1986), and it is irreversible. Drawing a regression line on this maximum will yield unrealistically high estimates of erosion. For the Anadarko basin in Oklahoma, the erosional estimate derived in this manner is greater than the entire Mesozoic and Cenozoic section (Pawlewicz, 1989). This approach is useful in Paleozoic basins, however, for studying the evolution of a basin, determining the timing of igneous intrusions and the onset of overpressuring and overthrusting, and for interpreting discontinuous R_m profiles (Katz and others, 1988; Law and others, 1989).

Coal is made of up to 90 percent or more vitrinite. Most coal is formed from plant material by diagenetic alteration involving bacteria, chemical activity, pressure and, primarily, heat. Though there is evidence for land plants existing from the pre-Silurian (Gray and others, 1982), vitrinite is, at best, rare and unequally distributed in lithology and facies regardless of age. For this reason additional organic entities are analyzed to broaden the application of petrography for thermal maturation determination. Some of these entities are chitinozoans (Goodarzi, 1985), graptolites (Kurylowicz and others, 1976; Goodarzi and Norford, 1985; Kemp and others, 1985; Goodarzi, 1984), scolecodonts, and solid bitumens (Curiale, 1986; Bertrand, 1990). Bertrand and Heroux (1987) compared the former three and found a depth-reflectance relation for each type of zooclast, but not between the individual zooclasts. They noted that reflectance results for the zooclasts should not be pooled for the evaluation of thermal maturity. Refining earlier work, Bertrand (1990) found that (1) chitinozoan and telinite (cell wall of structured vitrinite) reflectances are similar, (2) scolecodonts are always less reflecting than chitinozoans, and (3) zooclast reflectances converge and become similar to that of vitrinite with increasing maturation. Bustin and others (1989), in a laboratory study, demonstrated a direct correlation between maximum and random reflectance of graptolites and vitrinite.

Solid bitumens are ubiquitous in distribution and variety (Gentzis and Goodarzi, 1990). During burial, solid bitumens undergo irreversible chemical changes analogous to those of vitrinite. However, correlation of reflectance of solid bitumens and of vitrinite is imprecise. Regression lines for vertical profiles for solid bitumen and vitrinite intersect near 1.0 to 1.1 percent reflectance. Below 1.0 percent the reflectance of solid bitumen is less than, and above that value more than vitrinite. A susceptibility to alteration by deasphalting, water washing, biodegradation, and oxidation (weathering) reduces the utility of bitumen for maturation studies, as does its tendency to form fine-grained mosaic structures during rapid heating. The mosaic structures ruin the surface for reflectance measurements. Despite numerous shortcomings, the measurement of reflectance of solid bitumen is useful. Because vitrinite reflectance is the benchmark maturity indicator, mathematical equations have been derived to approximate the relation among vitrinite, bitumen, and zooclast reflectance (Bertrand and Heroux, 1987).

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Clay Minerals as Geothermometers—Indicators of Thermal Maturity for Hydrocarbon Exploration

By Richard M. Pollastro[1]

INTRODUCTION

Clay minerals provide information on the burial and thermal history of sedimentary rocks that is useful in the exploration, evaluation, and production of hydrocarbons. Over the past decade or so, empirical relations between clay minerals and temperature have provided a basis for their use as geothermometers. The utility of clay-mineral geothermometry has been applied mainly to diagenetic, hydrothermal, and metamorphic settings, in an attempt to better understand the thermal histories of ore and mineral formation, migrating hydrothermal fluids, and hydrocarbon source beds. Several clay minerals, particularly illite, mixed-layer illite/smectite (I/S), chlorite, kaolinite, and corrensite, are indicators of specific temperatures or temperature ranges (Hoffman and Hower, 1979). This report only discusses the current research status and activities related to clay-mineral geothermometry. In addition, I will demonstrate the utility of the method by presenting a case history where the I/S geothermometer has been applied successfully to a known petroleum system, the Niobrara(!) in the Denver basin and adjacent areas (table 1). In this example, the I/S geothermometer is applied regionally to correlate and predict the various degrees of thermal maturity in a formation that is both a petroleum source and reservoir rock and currently a major target for horizontal drilling.

CURRENT RESEARCH AND EVENTS

In USGS Bulletin 1912 (Magoon, 1989), I discussed briefly the state of research and presented an extensive bibliography on applications of clay mineralogy with particular attention to clay-mineral geothermometers (Pollastro, 1989). Since publication of Bulletin 1912, additional studies have been published, and symposia have been organized, on the subject of clay-mineral geothermometry; at the end of this report, an updated "Selected References" includes papers on this subject omitted from Pollastro (1989).

Following a special symposium held at the Rocky Mountain Section meeting of AAPG in October 1989, Nuccio and Barker (1990) published a volume entitled *Applications of Thermal Maturity Studies to Energy Exploration.* In that volume, I reviewed the concept, methods, and basic temperature models of the I/S geothermometer (Pollastro, 1990).

Two symposia have been organized recently on the reactions, processes, and applications of clay minerals for geothermometry. In July 1990, a conference on "Phyllosilicates as Indictors of Very Low Grade Metamorphism and Diagenesis" was held at the University of Manchester, United Kingdom. The conference was cosponsored by the International Geological Correlation Programme (IGCP), Project 294 (Very Low Grade Metamorphism), and the Clay Minerals and Metamorphic Studies Groups. About 35 oral and 18 poster papers were presented to over 120 participants. The conference focused on the chemical and physical processes related to expandability, illitization, and "crystallinity" measurements of illite and I/S, all which are common measurements used in clay-mineral geothermometry. Few papers were presented on specific temperature models for clay-mineral geothermometry or on comparison of temperatures derived from clay minerals to those for the maturity of organic matter. Selected papers from the conference will appear in future issues of *Clay Minerals* and *Journal of Metamorphic Geology.*

In October 1991, a special symposium at the 28th Annual Meeting of the Clay Minerals Society in Houston, Texas, entitled "Clay Geothermometers and Geochronometers," was convened by Eric Eslinger and Reed Glasmann. Titles for the program included presentations on case-history studies, reaction kinetics and mechanisms, and clay-isotope geothermometers. A total of 28 oral and 20 poster papers were presented.

In my recent review of the concept and utility of I/S geothermometry (Pollastro, 1990), I proposed two simple models for the I/S geothermometer: (1) a short-

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life geothermal model (<2 million years of heating) typical of very young sediments and modern hydrothermal systems, and (2) the model of Hoffman and Hower (1979), which pertains to older rocks and geothermal settings, particularly long-term, progressive burial diagenetic sequences and basins ranging in age from about 2 to 300 million years. Several case histories were presented in the paper to develop and support the temperature models.

Most recently, Elliot and others (1991) studied the smectite-to-illite reaction in bentonites from cores and outcrops of the Upper Cretaceous Mowry Shale and Niobrara Formation, Denver basin. They found that both the percent illite layers and K-Ar ages of I/S increase with increasing depth of burial. Mathematical models showed an overall fifth-order kinetic expression for the formation of illite. They concluded that, for most of the basin, the data are compatible with I/S having been formed in response to increased temperature from progessive burial because the oldest K-Ar ages of I/S are from the deepest buried I/S along the basin axis. In addition, I/S from bentonites in core from the Wattenberg gas field was the most illitic and among the oldest measured; these data are in agreement with anomalously high temperatures suspected in the Wattenberg field from previous studies of geothermometers based on organic matter (Rice, 1984; Higley and others, 1985, this volume)· and clay minerals (Pollastro and Scholle, 1986a, b).

APPLICATION TO THE NIOBRARA FORMATION, DENVER BASIN

The utility of I/S geothermometry is best shown using a study on the Niobrara Formation for the following reasons: (1) the Niobrara Formation in the Denver basin and adjacent areas is both a petroleum source and reservoir rock; (2) well-documented, progressive diagenetic changes occur relative to increased depth of burial and temperature that affect both the reservoir quality of the chalks and the type of indigenous hydrocarbons (microbial gas versus oil) produced (Pollastro and Scholle, 1986a); and (3) within the past five years, the overall success of the many horizontal wells drilled, particularly in fractured, organic-rich, thermally mature chalk or chalky shale reservoirs, has rekindled interest in the Niobrara Formation throughout the Rocky Mountain region as an exploration target for oil.

Although an earlier version of an I/S geothermometry map of the Niobrara in the Denver basin and adjacent areas has been published (Pollastro and Scholle, 1986a, b; Pollastro, 1990), I have recently updated, modified, and added data from about 20 wells to the current version (fig. 9). For example, data from the Silo field in southeastern Wyoming, where several horizontal wells in the Niobrara are at various stages of completion, are included in this revised version. Additionally, localities where transitional stages of I/S occur are identified.

The concept and the model used in this study are simple; I/S in bentonite beds from the Niobrara Formation and basal Pierre Shale is used to predict the type of hydrocarbons sourced by organic-rich chalk and chalky shale of the Niobrara. On the basis of X-ray powder diffraction profiles and the model of Hoffman and Hower (1979), randomly interstratified I/S (commonly referred to as R0 I/S) is assumed stable below temperatures of about 100°C. At burial temperatures of about 100-110°C, random or R0 I/S is converted to a short-range ordered I/S (referred to as R1 I/S); thus, only ordered (R>0) I/S is present above this temperature range in older (>2 million years) basin settings (see review by Pollastro, 1990). This study, and that recently reported by Elliott and others (1991), found few inconsistencies in I/S ordering among the several hundred samples from numerous well and outcrop localities.

The temperature range of 100-110°C for the random-to-ordered I/S transition is generally coincident with temperatures for the onset of peak (or main phase) oil generation in rocks of Late Cretaceous through early Tertiary age (Tissot and Welte, 1984, p. 180). These relations provide much of the basis for predicting hydrocarbon maturity within the Niobrara from I/S geothermometry. Additionally, microbial methane (an immature gas generated at low temperatures by the decomposition of organic matter by anaerobic microorganisms) is produced from the Niobrara in areas where burial temperatures never exceeded 75°C (Rice and Claypool, 1981). The I/S geothermometer is, therefore, especially useful for Niobrara rocks because it outlines areas of different degrees of thermal maturity as related to hydrocarbon generation. Areas with little or no potential, that is, those where maximum burial conditions were either too hot for microbial gas or too cool for thermogenic oil and(or) gas production, and probably between about 75°C and 100°C, can also be interpolated from I/S ordering and well production data. Areas that are potential targets for horizontal wells in thermally mature, fractured, Niobrara oil reservoirs should, therefore, contain only ordered I/S in bentonites.

Figure 9 is the updated version of the I/S geothermometry map applied to maturity of hydrocarbons generated within the Niobrara Formation. Random I/S in bentonite indicates areas of maximum burial temperatures for Niobrara rocks <100°C, whereas ordered I/S indicates areas where the Niobrara has been buried to temperatures >100°C and is thermally mature with respect to oil generation. Similarly, transitional I/S [localities where I/S is in the initial or transitional stage of converting from random to ordered I/S (see Pollastro and Martinez, 1985; Whitney and Northrop, 1988)] probably

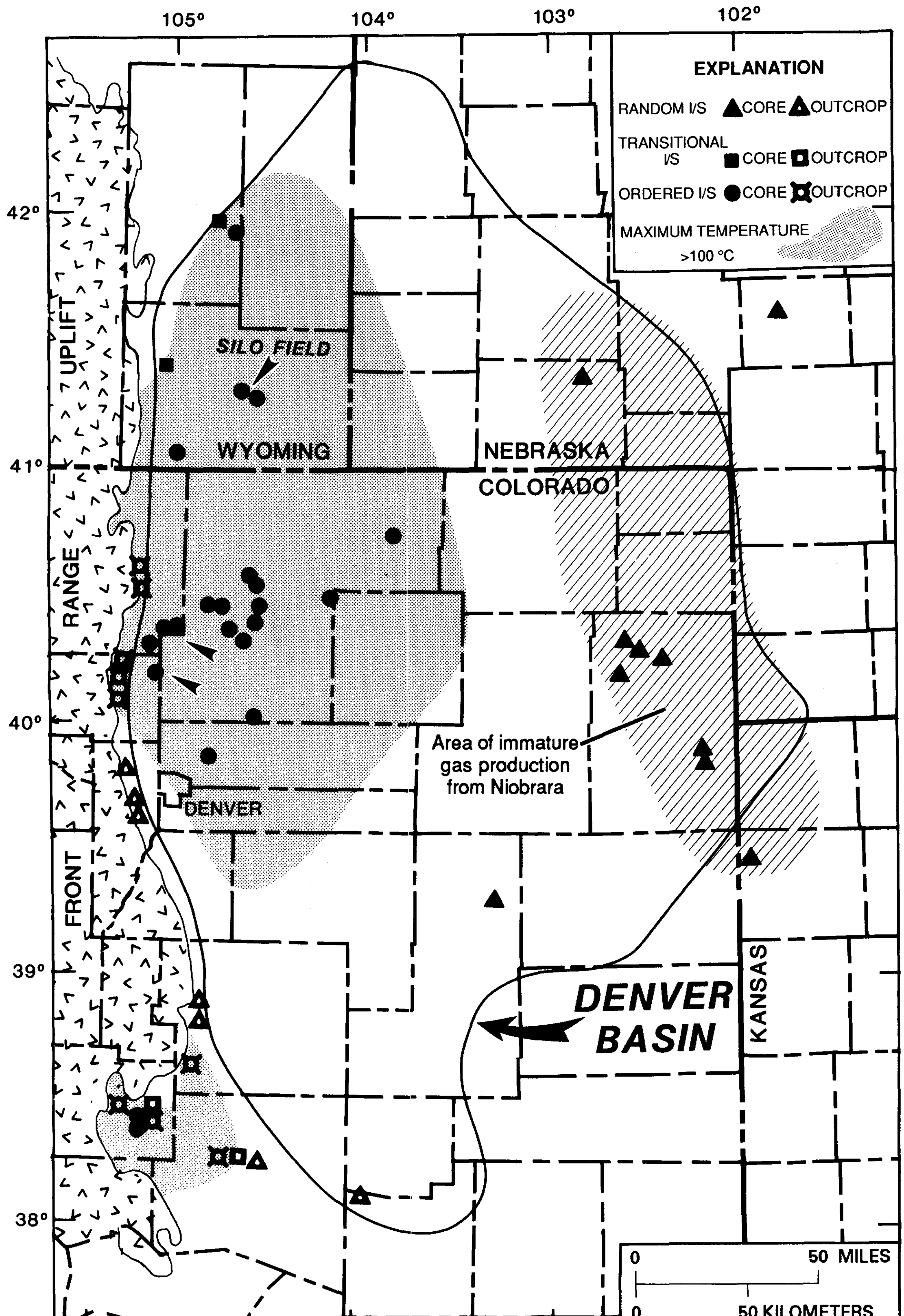

Figure 9. Geothermometry map as an indicator of thermal maturity and hydrocarbon type for the Niobrara Formation, Denver basin, Colorado. Temperature determined from the degree of ordering of illite/smectite (I/S) clay in bentonite as interpreted from X-ray powder diffraction profiles from samples of outcrop (open symbols) and core (solid symbols). Area of current microbial gas production from the Niobrara Formation is shown. Small arrows point to areas targeted for horizontal wells.

indicates maximum burial temperatures near 100°C (perhaps about 90–100°C) and can be interpreted as marginally mature with respect to oil generation. The area of current microbial gas production from Niobrara rocks is also indicated on figure 9 as the area of immature gas production.

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Influence of Regional Heat Flow Variation on Thermal Maturity of the Lower Cretaceous Muddy ("J") Sandstone, Denver Basin, Colorado

By Debra K. Higley, Donald L. Gautier, *and* Mark J. Pawlewicz[1]

INTRODUCTION

Vitrinite isoreflectance (R_m) contours delimit regional variation in levels of thermal maturity for hydrocarbon (HC) source rocks adjacent to the Lower Cretaceous Muddy ("J") Sandstone in the Denver basin (fig. 10). Variation results from areal differences in burial depth, heat flow, and basin hydrodynamics. Thermal maturity trends also suggest the occurrence of one or more heating events, one of which may be associated with the Late Cretaceous Laramide orogeny.

The Denver basin is an asymmetrical Laramide structural basin with a gently dipping eastern flank and a steeply dipping western flank; isoreflectance contours terminate against the Front Range uplift (fig. 10). The basin axis is approximated by a line connecting Denver, Colorado, and Cheyenne, Wyoming. Most Muddy ("J") Sandstone oil and gas fields are located on the shallow eastern flank of the basin. The Wattenberg gas field is enclosed by the 0.9 percent R_m contour and is located along the northeastern extension of the Colorado Mineral Belt (Sonnenberg and Weimer, 1981).

The "J" sandstone is an informal economic unit of the Muddy Sandstone. About 90 percent of the 800 million barrels of oil and 1.2 trillion cubic feet of gas (tcfg) produced from the Denver basin has been from the "J" sandstone. This predominantly nearshore marine, deltaic, and valley-fill sandstone was deposited about 99 to 97 million years ago (Ma) during a regression of the Cretaceous epicontinental seaway (Kauffman, 1977, Obradovich and Cobban, 1975, Weimer, 1984, Weimer and others, 1986). The Muddy ("J") Sandstone is bounded by marine shales, which are probably the main source rocks for oil and gas produced from the Muddy ("J") Sandstone (Clayton and Swetland, 1980). These are the underlying Skull Creek, and overlying Mowry and Graneros Shales; these shales were sampled at 14 outcrop locations and from cores of 42 wells for R_m analysis (Higley and others, 1985).

Acknowledgments.—Roy Gallop of Core Laboratories, Denver, Colorado, supplied core data. Many oil companies generously released well data. Sources of R_m include unpublished data from Ernest Jones, Dudley Rice, and Jerry Clayton; their assistance is appreciated.

ISOREFLECTANCE TRENDS

Thermal maturation of HC source rocks depends largely on increasing depth of burial and areal variation in Denver basin heat flow. R_m increases almost exponentially with increasing burial depth in the Colorado portion of the basin, ranging from 0.41 percent at 4,900 ft (1,500 m) depth to 1.51 percent at 7,800 ft (2,400 m)(Higley and others, 1985). The correlation coefficient for the linear regression of depth versus log R_m is –0.64 for the Colorado samples (fig. 10). There is no correlation between depth and R_m for samples located in Nebraska and Wyoming (+0.26). Correlations are 0.86 to 0.93 for the least-squares regressions of down-hole depth versus log R_m for the four wells shown on figure 11. Differences in slopes of the lines result mainly from areal difference in heat flow. Poorer correlations for the Muddy ("J") Sandstone data than for the four wells results from variable rates of current and probable paleoheat flow across the basin, and also from influence of different thicknesses of eroded Tertiary sediment on computed maximum burial.

In oil-prone types of organic matter, an R_m range of about 0.6 to 1.35 percent is commonly considered to be the main zone of oil generation. Thermogenic gas is the predominant product above an R_m of approximately 1.35 percent (Waples, 1980). Source rocks with R_m values less than 0.60 percent are usually considered to be thermally immature for oil generation in the types II and III kerogen from which Muddy ("J") Sandstone oil and

[1] U.S. Geological Survey, Denver, Colo.

gas is produced (Clayton and Swetland, 1980). The 0.6 percent isoreflectance contour line corresponds to a present-day depth of about 6,000 ft (1,800 m) in the Denver basin. Oil and gas production in areas of lesser R_m values suggests migration of oil from deeper and hotter areas of the basin. Studies of Cretaceous oils by Clayton and Swetland (1980) show that much of the Muddy ("J") Sandstone oil in the southeastern quarter of figure 10 originated deeper in the basin.

In general, the lowest R_m values are on the shallower eastern flank of the basin and at the Muddy Sandstone outcrops along the western flank (excluding the area directly west of the Wattenberg field). Cretaceous and older rocks that crop out on the west side of the basin were uplifted during the Laramide orogeny, which began about 68 Ma and ended about 50 Ma (Trimble, 1980; Tweto, 1975, 1980). Because this uplift preceded the maximum burial depth attained in other parts of the basin, R_m values of outcrop samples are generally much less than in samples immediately basinward. Maximum burial for Muddy ("J") Sandstone source rocks in most of the basin was attained during the late Tertiary (Tainter, 1984; Higley and Gautier, 1988). Erosion of Tertiary and Upper Cretaceous rocks across the basin is associated with broad uplift of the Great Plains during the last 7 to 10 million years (Epis, 1973, Izett, 1973, Lachenbruch and Sass, 1977, Taylor, 1973, Zoback and Zoback, 1980). During this period of time a minimum 1,000 ft (300 m) and as much as 5,500 to 6,500 ft (1,700–1,900 m) of rock was removed (Higley and Schmoker, 1989;

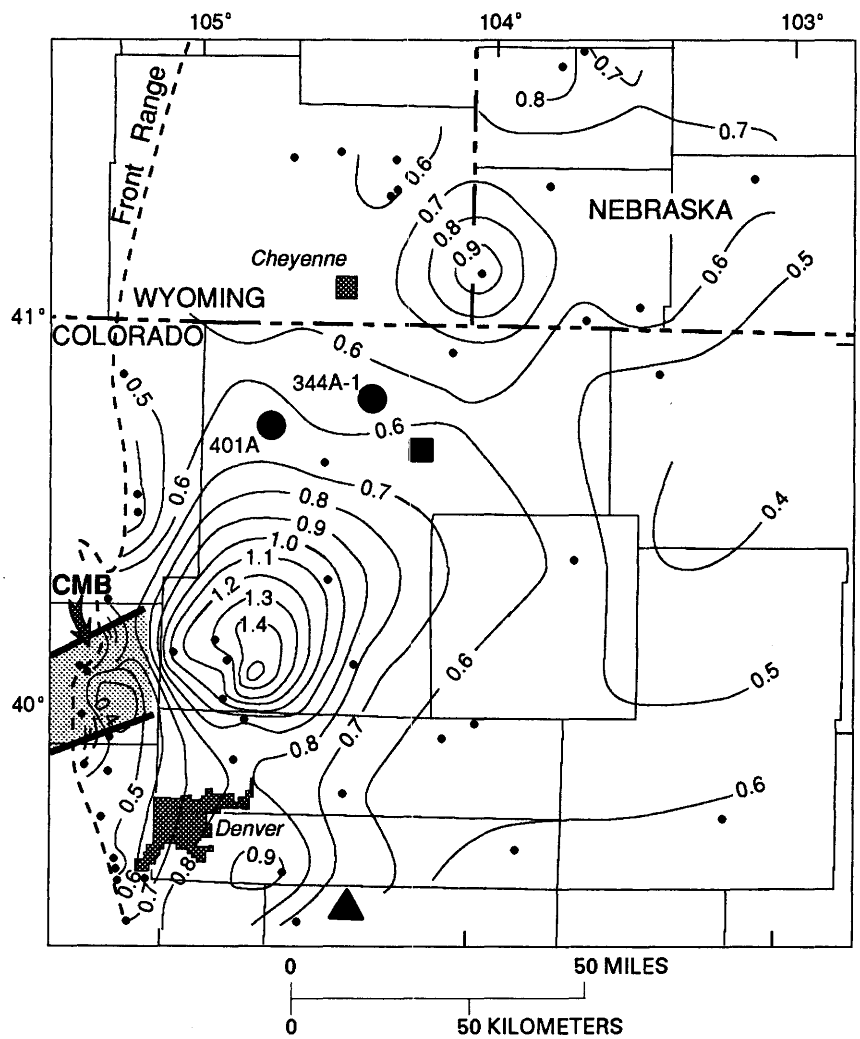

Figure 10. Isoreflectance contour map of the Lower Cretaceous Muddy ("J") Sandstone in Denver basin. Wattenberg field is approximately in "bulls eye" of 0.9 to 1.5 percent R_m. Contour interval is 0.1 percent R_m. Small solid dots are R_m sample locations; large symbols are locations for Sohio well No. 12-7 Whitehead (triangle) and Amoco wells Nos. 1 Champlin 562A-1 (square) and 1 Champlin 401A and 344A-1 (dots). Dashed line is western boundary of Denver basin. Northeasterly trend of Colorado Mineral Belt (CMB) is shown.

L.C. Price, oral commun., 1991). Estimates of erosion are based on stratigraphic reconstruction and on downhole thermal maturity plots of Cretaceous through Tertiary strata (fig. 11).

The highest R_m values are in the Wattenberg gas field. The 1.3 percent R_m contour line approximates the onset of thermogenic gas generation; higher R_m values suggest that some of the gas is thermogenic in origin. Gas-prone type III kerogen also contributes to the more than 0.57 tcfg (to 1/89) produced from the Wattenberg field. Samples collected within the gas generation zone range from depths of 7,000 to 8,000 ft (2,100–2,400 m).

Values of R_m in the Wattenberg field are anomalously high when compared to surrounding areas, even when reconstructed to maximum depths (Higley and Schmoker, 1989). In addition, the geothermal gradients are also anomalously high. This high heat flow probably results from several processes; three of these are (1) influence of lateral and upward moving fluids (Meyer and McGee, 1985), (2) possible effect of broad regional uplift, and (3) areal variation in heat conductivity of rocks and pore fluids.

There is evidence of one or more heating events, probably associated with Laramide reactivation of northeast-trending Precambrian basement faults of the Colorado Mineral Belt. Reactivation of these faults during and following the Laramide orogeny (Haun, 1968, Hoblitt and Larson, 1979, Sonnenberg and Weimer, 1981, Weimer, 1984) may have influenced the thermal maturity of overlying sediments, both through increased heat flow and by more efficient heat transfer through associated fracture and fault systems. Additional support for the mineral belt heat source includes this evidence: (1) Anomalously large R_m values occur in outcrop samples directly west of the Wattenberg field; (2) isoreflectance contours in Paleozoic formations of southwest Nebraska mimic the Muddy ("J") Sandstone source rock anomaly (J. Clayton, oral commun., 1990) and are on trend with the mineral belt; (3) laccolithic intrusions along the mineral belt are dated Laramide and younger (Armstrong, 1969; Bryant and Naeser, 1980; Hoblitt and Larson, 1975); and (4) conodonts of the Mississippian Leadville Limestone exhibit anomalously high color alteration index (CAI) values within the mineral belt. This CAI anomaly may be associated with Laramide hydrothermal flow (Bridges and McCarthy, 1990).

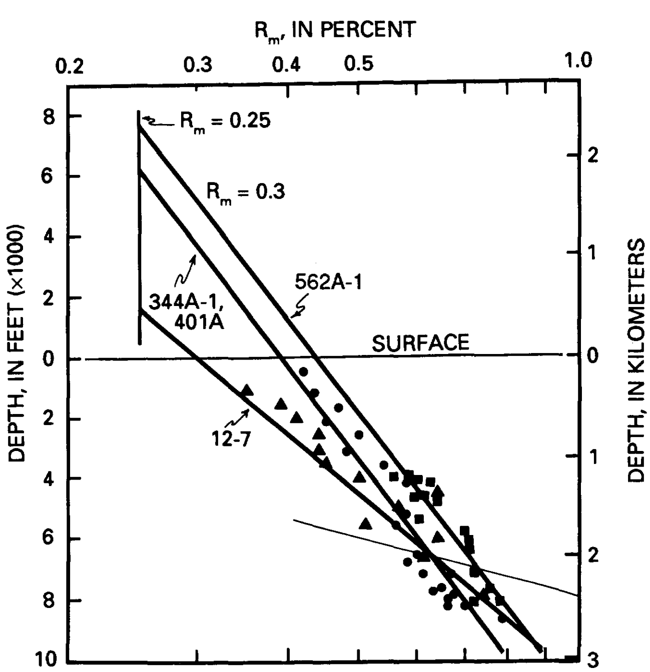

Figure 11. Isoreflectance sample depths and correlation curves (extrapolated above ground surface) for Sohio well No. 12-7 Whitehead (triangles) and Amoco wells Nos. 1 Champlin 562A-1 (squares) and 1 Champlin 344A-1 and 401A (dots) (modified from Tainter, 1984). Extrapolation of curves to a postulated above-surface R_m of 0.25 percent yields about 2,000 to 8,000 ft (610–2,400 m) of eroded sediment thickness. Correlation curve (thin line) of "J" sandstone data set is also shown.

While basin R_m trends are apparent, scatter in data is considerable. Some of the scatter results from uncertainty in the measure of vitrinite reflectance. Values of R_m may be affected by the presence of oxidized or recycled organic matter and inertinite macerals, which have reflectance levels greater than vitrinite. These macerals are common in the Nebraska and Wyoming samples (fig. 10) and may have influenced R_m values. Some of the anomalous R_m data may be due to sampling; oil fields in the Rocky Mountain region are hotter than adjacent nonproducing areas (Meyer and McGee, 1985); this may be related to basin hydrodynamics and to the low thermal conductivity of hydrocarbons. Effects of the basin deep west of Cheyenne, Wyoming, are undocumented because of lack of data. However, clay mineral and radiometric work by Elliott (1988) suggests that source rocks here are within the oil generation window and may be within the gas generation window.

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Thermal Maturity of the Mesaverde Group, Uinta Basin, Utah

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INTRODUCTION

The level of thermal maturity achieved by hydrocarbon source rocks is one of the most important factors controlling petroleum generation. Thermal maturity studies also play an important role in assessing reservoir diagenesis, timing of structural movement, burial history reconstruction, fluid movement, and porosity prediction. This paper summarizes the thermal maturity of the Mesaverde Group (Upper Cretaceous) in the Uinta basin, Utah (fig. 12). Using vitrinite reflectance (R_m), two maps show the R_m of rocks at the base and top of the Mesaverde Group. A map of elevation to 0.75 percent R_m illustrates the position for onset of gas generation for type III kerogen and the formation in which it occurs. Cross sections illustrate the stratigraphy, types of kerogen, levels

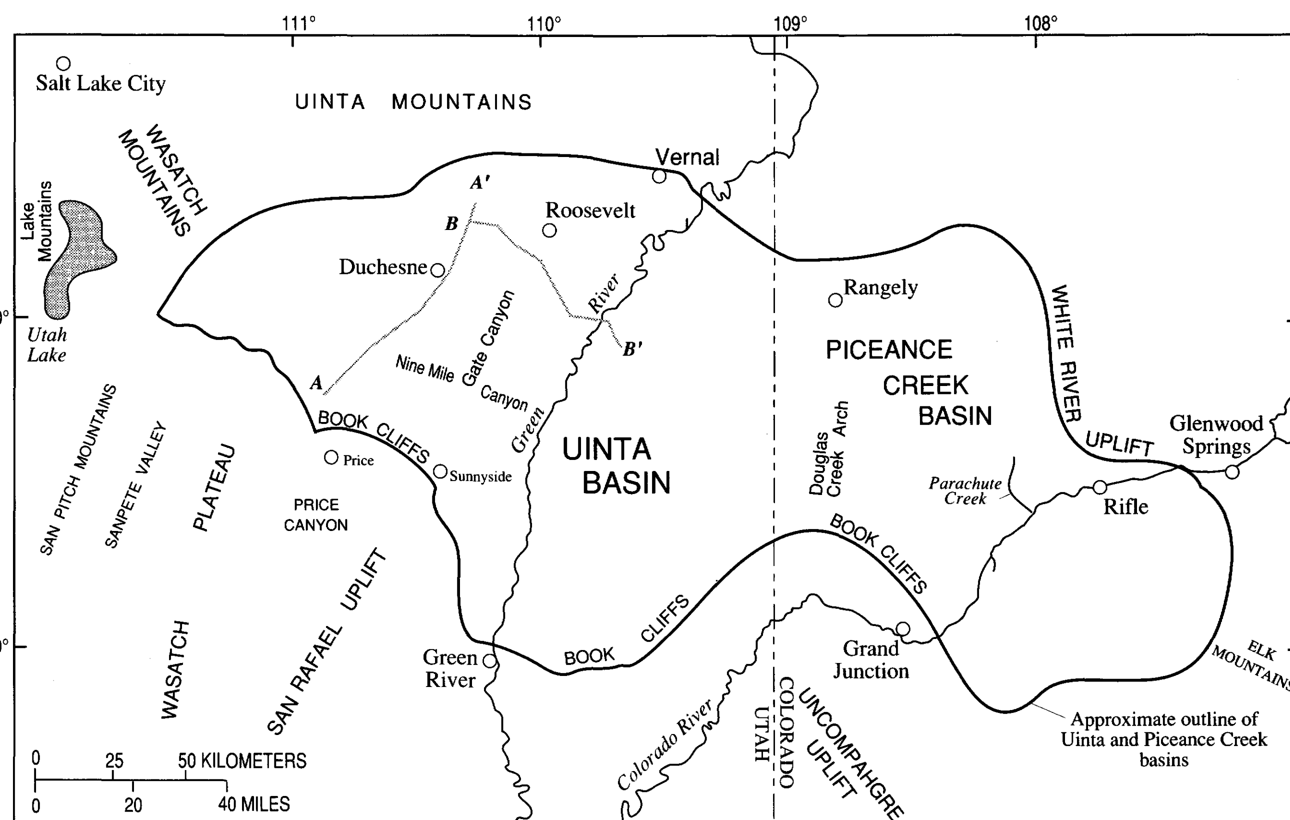

Figure 12. Index map of Uinta and Piceance basins in Utah and Colorado. Locations of cross sections *A-A'* (fig.13), *B-B'* (fig. 14), and Book Cliffs are shown.

[1] U.S. Geological Survey, Denver, Colo.

of thermal maturity, and the position of hydrocarbon-producing zones of lower Tertiary and Upper Cretaceous formations within the Uinta basin.

This study is based on data collected as part of the U.S. Department of Energy's Western Tight Gas Program and the U.S. Geological Survey's Onshore Oil and Gas and Evolution of Sedimentary Basins Programs. The data base comprises several hundred core and cutting samples of coal and carbonaceous shale that were analyzed for vitrinite reflectance and Rock-Eval pyrolysis. A large part of the present study is based on Johnson and Nuccio (in press), Nuccio and Johnson (1986, 1988), and the first author's unpublished data.

KEROGEN TYPE AND SOURCE ROCK POTENTIAL

Several models have been developed relating the generation of hydrocarbons to types of kerogen and thermal maturity (Tissot and others, 1974; Dow, 1977, Waples, 1980, 1985). Three general types of kerogen have the potential, under optimum conditions, to generate hydrocarbons: type I, alginite—sapropelic or lipid-rich; type II, exinite—phytoplankton, zooplankton, and other microorganisms, and type III vitrinite—huminite (terrestrial plant debris).

Type I kerogen is hydrogen-rich, occurs primarily in marine and lacustrine rocks, and generates mainly oil during catagenesis. The onset of oil generation from type I kerogen varies depending on the model one chooses. There is no absolute point at which hydrocarbon begins to be generated, and it probably begins over a range of R_m values depending on the specific type of organic matter. Dow (1977) used 0.50 percent R_m as the onset of oil generation for type I kerogen, while Anders and Gerrild (1984) and Tissot and Welte (1984) used 0.70 percent R_m.

Type II kerogen occurs mainly in marine rocks, but can occur in lacustrine rocks as well, and generates mostly oil during catagenesis. Waples (1985) states that oil generation begins over a range of R_m values of about 0.45 to 0.50 percent for high-sulfur kerogen to 0.60 percent for "typical" type II kerogen.

Huminite and vitrinite or type III kerogen is oxygen-rich and hydrogen-poor, occurs mainly in terrestrial, marginal lacustrine, or marginal marine rocks, and generates mainly methane gas during maturation. For type III kerogen, vitrinite reflectance is the best and most widely used measure of thermal maturity. Two important R_m thresholds, 0.75 and 1.10 percent, are used to define regions of gas generation from type III kerogen. An R_m of 0.75 percent represents the maturity required for the onset of significant gas generation (Juntgen and Karweil, 1966; Juntgen and Klein, 1975). Gas accumulations found in rocks with an R_m less than 0.75 percent contain either early microbial gas or thermal gas migrated in from more mature source rocks. In the Piceance basin, it appears that low-permeability Mesaverde rocks have negligible gas production where the Mesaverde has an R_m less than 0.73 percent (Johnson, 1989; Johnson and others, 1987). An R_m of 1.10 percent represents the level of maximum gas expulsion from type III kerogen (Meissner, 1984). The upper limit of maturity for gas preservation is still unknown, but could be as high as 4.0 percent R_m (Waples, 1980).

Types I, II, and III kerogen are present in the Green River Formation (Eocene), and these rocks have generated large amounts of oil and gas in the Uinta basin (cross section *A–A'*, fig. 13; *B–B'*, fig. 14). The thick Mancos Shale (Upper Cretaceous) is probably similar to the Mancos in the Piceance basin, where it contains significant amounts of types II and III kerogen and has generated oil and gas (Johnson and Rice, 1990). The nonmarine to nearshore marine Mesaverde Group contains dominantly type III kerogen and has the potential to generate large amounts of methane gas (Pitman and others, 1987).

R_M MAP OF BASE OF MESAVERDE GROUP

The R_m map at the base of the Mesaverde Group shows a trend of increasing maturity from south to north (fig. 15). This trend generally follows the structural configuration of the base of the Mesaverde; this indicates maturity was set prior to or during early stages of structural movement. In some areas, however, the R_m lines cut across structure indicating that maturity continued during or for some time after structural movement. Variation in heat flow could cause this crossing of R_m lines, but most likely toward the deepest part of the basin where the Tertiary overburden is thickest, and where the effects of structural movement and erosion are less, thermal maturity at the base of the Mesaverde continued during or after uplift and erosion which began 10 Ma. On the flanks of the basin, however, maturity may have been "frozen" at pre-structural levels.

Four R_m lines and three zones of hydrocarbon generation are shown in figure 15. The 0.65 percent R_m reference line shows the thermal maturity at the base of the Mesaverde around the edge of the basin. The areas of the basin that are not mature enough for significant gas generation (<0.75 percent R_m) are shown by the light stipple pattern. The 0.75 percent R_m line indicates the maturity for onset of significant gas generation from type III kerogen at the base of the Mesaverde. The area between 0.75 percent and 1.10 percent R_m (darker stipple) is the area of potential gas generation and accumulation in Mesaverde reservoirs. The area north of 1.10 percent R_m (darkest pattern) is the zone of maximum gas generation and expulsion. The upper limit of gas generation in the northern and deepest, undrilled part of the basin is currently unknown. The 0.65 percent and 1.50 percent R_m lines are for reference only.

The base of the Mesaverde is greater than 0.75 percent R_m over a large area of the Uinta basin. Except for the margins of the basin, where subsidence and amount of deposition were less, gas was probably being generated in Paleocene or early Eocene time as Tertiary sediments were being deposited. This generation continued until 10 Ma, when uplift and erosion caused regional cooling. Effects of uplift and erosion were not as great in the deepest part of the basin, and if temperatures were still great enough, and kerogen was available (not "cooked out"), gas generation may have continued after 10 Ma and may be actively generating today. It is likely that this gas was trapped in "tight reservoirs" throughout the generation history of the Mesaverde, and the areas of overpressuring in the basin today may mark the areas of active generation.

R_M MAP OF TOP OF MESAVERDE GROUP

The R_m map at the top of the Mesaverde Group also shows a trend of increasing maturity from south to north (fig. 16). R_m lines generally follow the structural configuration of the top of the Mesaverde, suggesting that the observed maturity was reached prior to or during

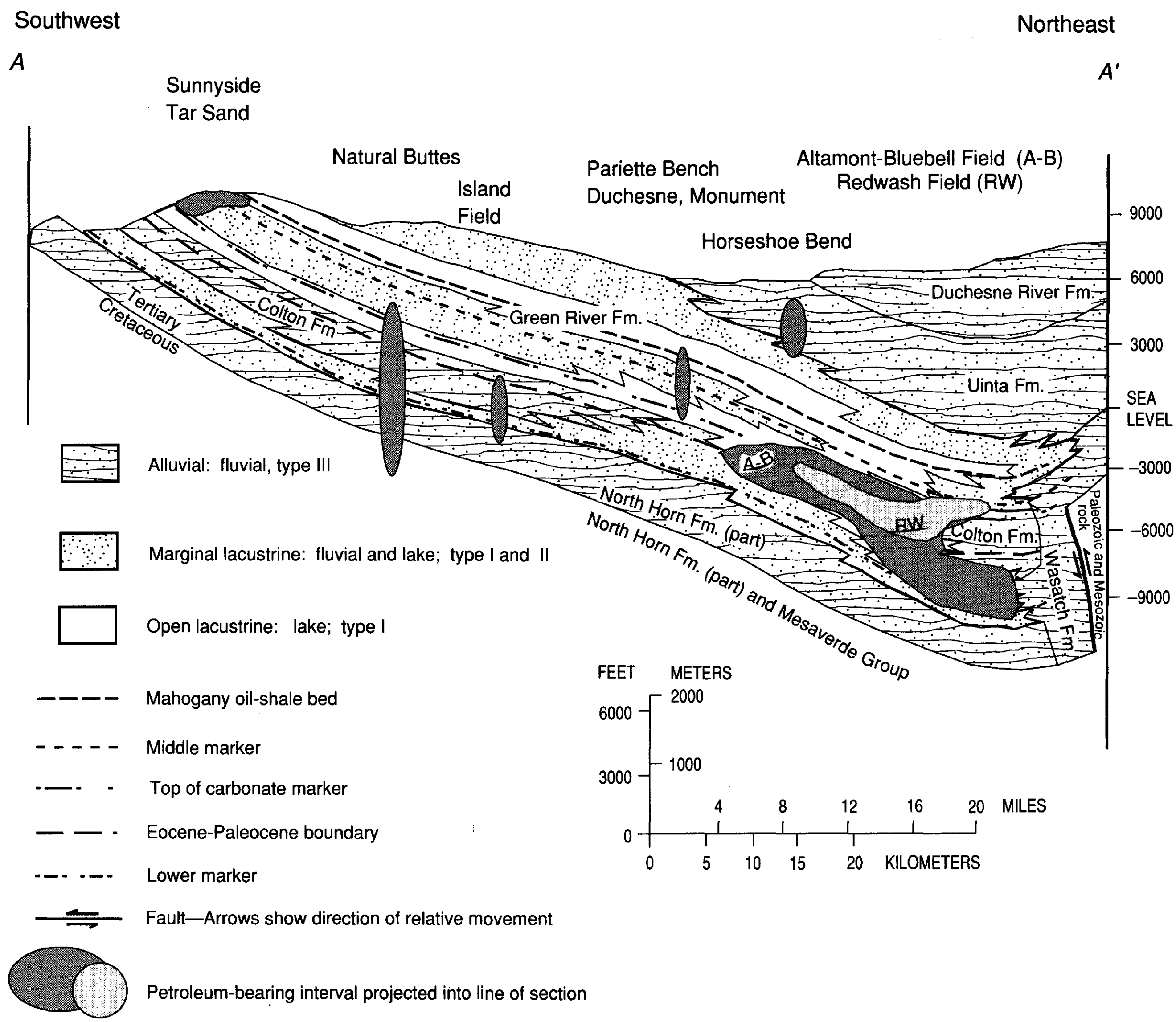

Figure 13. Generalized cross section *A-A'* from outcrops on southwest flank of Uinta basin, through Duchesne and Altamont-Bluebell oil fields, to north-central part of Uinta basin, Utah (modified from Fouch, 1975). Figure also contains commonly used subsurface stratigraphic markers, types of kerogen (types I, II, and III), and principal fields. Location of cross section on figure 12.

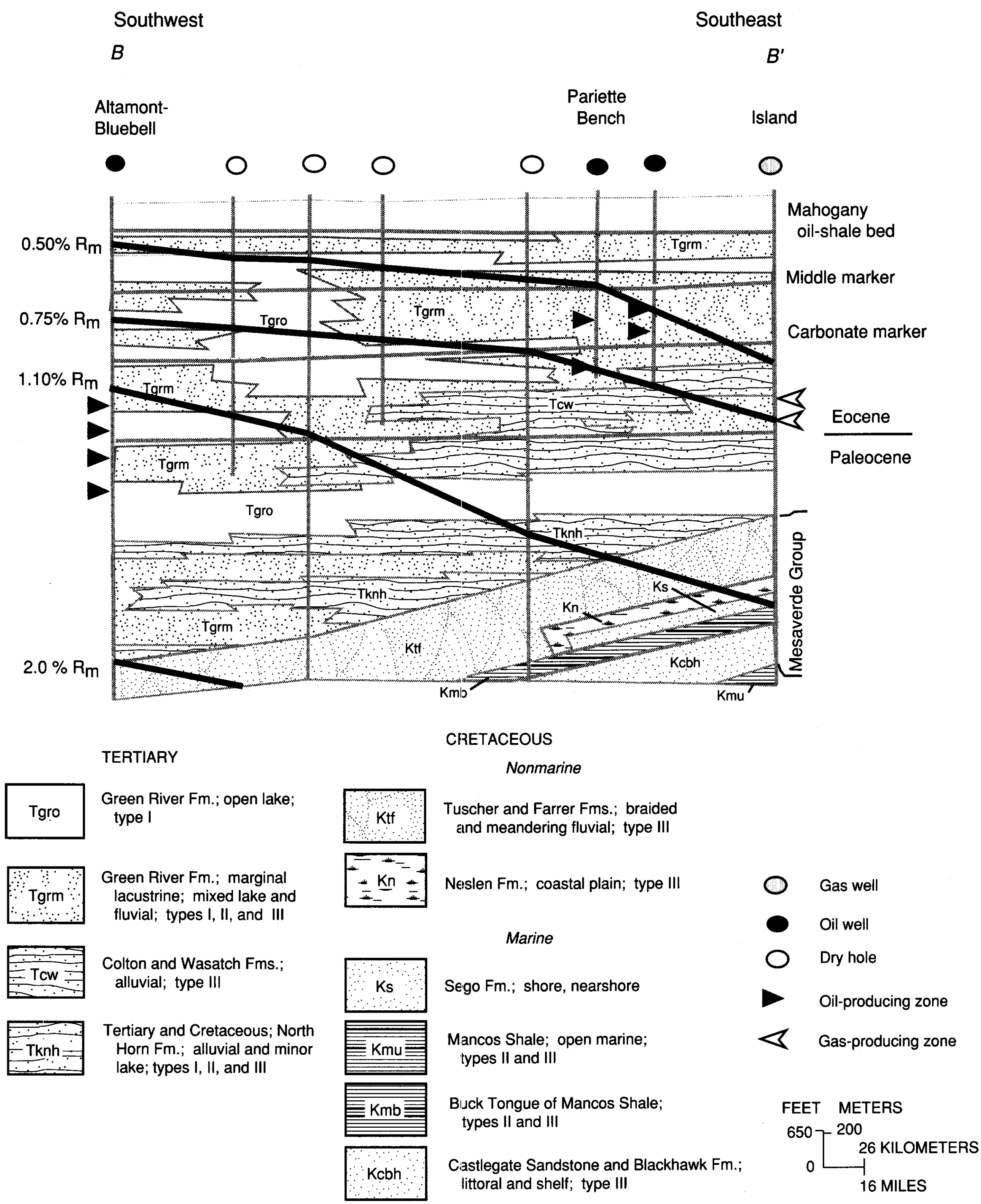

Figure 14. Cross section *B-B′* from Altamont-Bluebell area (deepest part of basin) southeastward to Island gas field. R_m isoreflectance lines and hydrocarbon-producing zones are superimposed on cross section. Types I, II, and III are types of organic matter in the rocks.

the early stages of final structural movement 10 Ma. As with the map for the base of the Mesaverde (fig. 15), R_m lines in some areas cut across structure. This indicates continued maturation during or after structural movement. R_m lines on the top of the Mesaverde Group equivalent to those at the base are located farther to the north, suggesting a larger area of less mature rock at the top of the Mesaverde. This pattern is a direct result of less depth of burial (up to several thousand feet) on the top of the Mesaverde.

Five R_m isoreflectance lines and three zones of hydrocarbon generation are shown in figure 16. The 0.50 percent and 0.60 percent R_m lines are for reference, and show the general maturity for the top of the Mesaverde where it crops out around the edge of the basin. For the area south of the 0.75 percent R_m line (light stipple pattern), one would not expect significant gas generation from source rocks located near the top of the Mesaverde. The area between the 0.75 percent and 1.10 percent R_m (medium stipple pattern) lines is the zone of significant

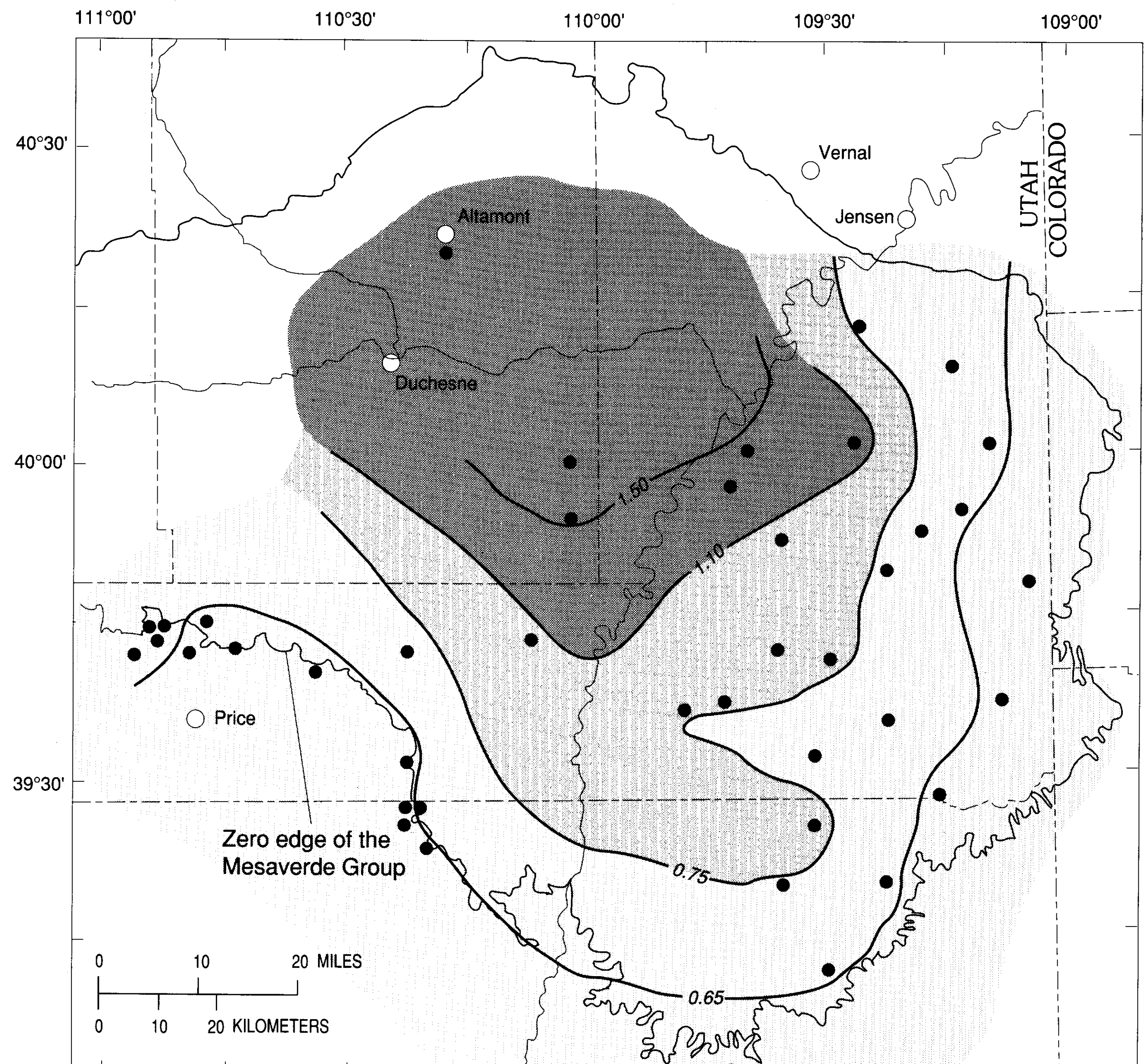

Figure 15. Vitrinite reflectance (R_m) map showing thermal maturity at base of Mesaverde Group, Uinta basin, Utah. Map indicates areas of no gas generation (<0.75 percent R_m or light stipple pattern), onset of significant gas generation (0.75–1.10 percent R_m or medium stipple pattern), and maximum gas generation and expulsion (>1.10 percent R_m or dark pattern). Black dots indicate location of bore-hole or outcrop sample.

gas generation, and the area north of the 1.10 percent R_m line (darkest pattern) is the zone of maximum generation and expulsion for type III kerogen source rocks near the top of the Mesaverde. The 2.0 percent R_m line is for reference only, but indicates maturity at the top of the Mesaverde in the most deeply drilled part of the basin. As discussed earlier for the base of the Mesaverde, the upper limit for gas preservation is poorly defined.

The areal extent of rocks with greater than 0.75 percent R_m is less for the top than that at the base of the Mesaverde and occurs further north in the deeper part of the basin. Again this pattern is due to less depth of burial on the top of the Mesaverde. Therefore, gas generation for the top of the Mesaverde began later than for the base, probably not until Eocene or Oligocene time. This timing agrees with Pitman and others (1987), who constrained timing of gas generation from the Upper Cretaceous Neslen and Blackhawk Formations to Oligocene and Miocene time. As with the base of the Mesaverde, gas generation continued through the Tertiary and was

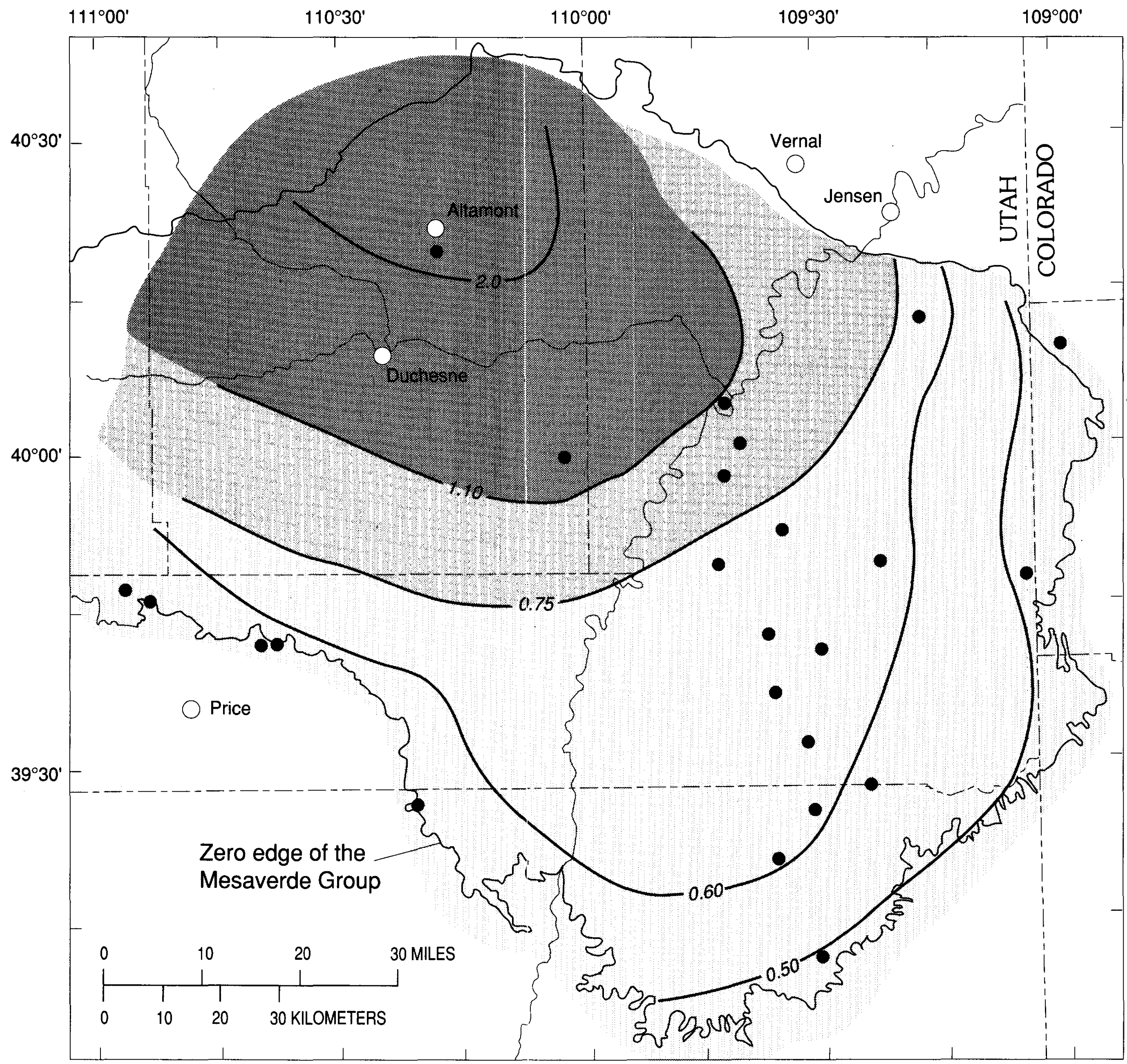

Figure 16. Vitrinite reflectance (R_m) map showing thermal maturity at top of Mesaverde Group, Uinta basin, Utah. Map indicates areas of no gas generation (<0.75 percent R_m or light stipple pattern), onset of significant gas generation (0.75–1.10 percent R_m or medium stipple pattern), and maximum gas generation and expulsion (>1.10 percent R_m or dark pattern). Black dots indicate location of bore-hole or outcrop sample.

being emplaced into nearby reservoirs. Since 10 Ma, gas generation ceased at the top of the Mesaverde horizon in many parts of the basin; however, in the deeper parts, active generation is still possible today.

MAP SHOWING ELEVATION TO 0.75 PERCENT R_M

Figure 17 is a map showing the elevation from sea level to the 0.75 percent R_m line; the threshold for significant gas generation. The 0.75 percent R_m line cuts across formation boundaries; it moves up stratigraphically to the north. For example, in the southernmost part of the basin, 0.75 percent R_m occurs in the Mancos Shale, whereas in the northern part of the basin near Altamont, 0.75 percent R_m occurs between the middle and carbonate markers of the Green River Formation (fig. 14). The reason for this upsection movement is related generally to the structural movements and variations of burial depth in the basin. After final movement, the basin flanks were higher, and due to erosion there was less

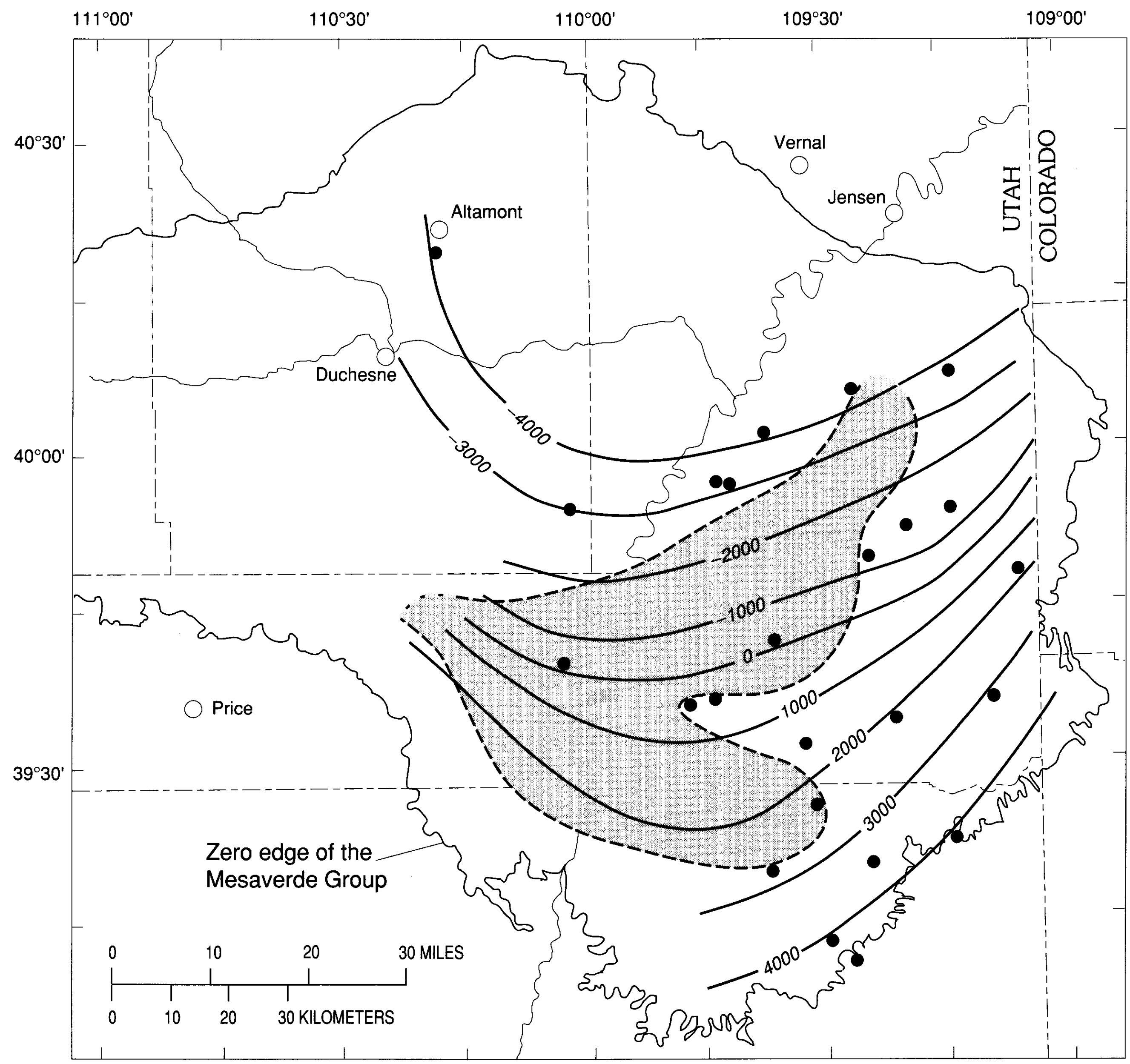

Figure 17. Elevation (in feet) relative to sea level of 0.75 percent R_m line (onset of significant gas generation), Uinta basin, Utah. Shaded area indicates where 0.75 percent R_m line occurs in Mesaverde Group. South and east of shaded area, line is in pre-Mesaverde Group rocks. North of shaded area, line falls within Tertiary rocks. Black dots indicate location of bore-hole or outcrop sample.

overburden present. However in the center of the basin, where the effect of uplift and erosion was less, and more overburden was present, the rocks continued to mature. This caused an apparent raising of the R_m lines to stratigraphically higher positions.

The shaded pattern in figure 17 represents the area where the elevation of the 0.75 percent R_m line occurs in the Mesaverde Group. This map is useful in that it approximates the elevation (easily converted to depth) one would drill to encounter the threshold for significant gas generation, and which formation it could be found in.

CROSS SECTION SHOWING R_M LINES AND PRODUCTION

Figure 14 shows R_m lines superimposed on a stratigraphic cross section through the Uinta basin. The cross section *B-B'* extends from the Altamont-Bluebell area (deepest part of the basin) southeastward to the Island gas field. As discussed earlier, the R_m lines climb stratigraphically going northward, toward the deeper part of the basin. The 0.50 percent R_m line shows where types I and II kerogens should be mature enough for oil generation. It is interesting to note that the oil-producing zones are found where mixed types I, II, and III kerogen and the optimum maturity range for oil generation (>0.50 percent R_m) occur. The 0.75 percent R_m line indicates where the onset of significant gas generation for type III kerogen should occur. Not surprisingly, the gas-producing zones coincide with type III kerogen and an R_m of around 0.75 percent. The 1.10 percent R_m line shows where maximum gas generation and expulsion would be found for type III kerogen. The 2.0 percent R_m line represents the level of thermal maturity for the top of the Mesaverde in the deeper part of the basin.

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NERSL—National Energy Research Seismic Library

By David J. Taylor[1]

Geology, a science dealing with the history of the Earth as recorded in its rocks, strives to visualize subsurface structure and stratigraphy. Early geologic information came mainly from extrapolation of surface geology into the subsurface and from rock samples brought up during drilling operations. The application of physics to geologic science offered new and better ways to see below ground level. The evolution of modern geophysical techniques, especially multichannel seismic-reflection imagery, now supplies earth scientists with clearer pictures of subsurface geology. The U.S. Geological Survey (USGS) started collecting multichannel seismic-reflection data in the early 1970's to provide its programs with suitable subsurface information. Much of this data, acquired directly or through contract, is information available in the public domain.

In the early 1980's Federal budgets for earth science research began to shrink, and money needed to acquire new seismic-reflection data became increasingly scarce. The inability to acquire new seismic data has started to jeopardize the ability of the USGS to thoroughly fulfill some of its key missions. A 1988 National Research Council (NRC) study of USGS energy-related programs recommended that the USGS develop a network of seismic-reflection data from both presently available and newly acquired seismic data (National Academy Press, 1988). The NRC report specifically stated that the USGS develop a scheme to catalog available seismic data and provide a means to access the data. In response to the NRC recommendations and the need to develop a data management policy for its digital multichannel seismic-reflection data inventory, the USGS established the National Energy Research Seismic Library, or NERSL, in late 1989.

A reliable picture of the subsurface is usually helpful when solving most geologic problems. The purpose of the NERSL is to provide earth scientists in government, industry, and academia with data needed to construct these pictures. Several critical USGS research programs, such as the Deep Continental Studies program, the Offshore Geologic Framework program, the Evolution of Sedimentary Basins program, the Geologic Risk Assessment program, and the Onshore Oil and Gas program, have benefited from having seismic data available to them. The aim in establishing a national seismic library is to supply researchers throughout the scientific community with data that are necessary but usually hard to obtain.

The NERSL being a repository for unprocessed and processed multichannel seismic-reflection data can provide raw materials not only to those trying to solve specific geologic problems but also to those who are conducting research in the development of new reflection seismic data processing techniques. Finding solutions to unusual geologic problems often drives the development of new technology. Therefore, supplying the data needed to solve geologic problems and stimulate development of new technology is another goal of the NERSL.

Regional grids of seismic-reflection data have provided USGS scientists with information leading to the formulation of new geologic concepts and the enhancement of previous work. A good example is the San Juan basin tectonic framework study under the Evolution of Sedimentary Basins program. Through purchase of proprietary information and contributions from private industry, USGS scientists were able to build a modest regional grid of seismic lines in the basin. Initially, a fault map of the thrusted northwestern edge of the basin was produced from the reprocessing and interpretation of the data (Taylor and Huffman, 1988). Using the larger grid of proprietary seismic data allowed this original interpretation to be extended and resulted in the creation of a basement fault map covering most of the basin area. This fault map was used to develop a story for the evolution of the San Juan basin and surrounding area (Huffman and Taylor, 1989). Correlation of the basement faults with the location of hydrocarbon production in the San Juan basin hints that movement along these faults through time may have influenced deposition creating the conditions needed to form accumulations of mineral and petroleum resources (Phelps and others, 1986; Huffman and Taylor, 1990). Similar USGS studies are in progress wherever seismic databases are available, and the objective of the NERSL is to supply the seismic data bases necessary to carry out these investigations.

[1] U.S. Geological Survey, Denver, Colo.

Other government and nongovernment agencies have large multichannel seismic-reflection data libraries. Cornell University's Consortium for Continental Reflection Profiling (COCORP) makes available to the public its inventory of deep seismic reflection data (Nelson, 1988). Most government-collected geophysical data is offered to the public through the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center (NGDC). There are also many small data brokerage firms operating that sell limited grids of proprietary seismic-reflection data. There has never been an attempt made to establish a national repository containing both field and processed digital seismic-reflection data collected from government and nongovernment sources which allows public access. All data released through COCORP, NOAA-NGDC, or private industry is distributed on some form of magnetic tape, and costly processing systems are usually required to read these tapes. A design objective for the NERSL is to allow those owning inexpensive computer systems access to the seismic data base. Since the repository will hold the actual unprocessed field data, and its corresponding processed version, there needs to be a widely available low-cost way for the scientist to examine the data. Therefore, processed data will be distributed on commonly used compact disks with read-only memory, or CD-ROM's.

Low-cost CD-ROM readers that can be attached to standard personal computers are now available. Software accessible on the CD-ROM will allow the scientist to display, in color or black and white, the processed seismic sections with a map showing the location of the data. The software will also let the user scale the data, zoom in to produce a detailed display on a chosen part of the data, and plot the data to a low-cost dot-matrix printer. A description of the data and instructions on using the software resides on the disk in a file that can be displayed or printed. This information is also available as a USGS Open-File Report (Hutchinson and others, 1990).

The NERSL CD-ROM has been designed to hold the actual processed digital information and not just scanned images of paper displays. The major advantage compared to the COCORP atlas or NOAA-NGDC notices is that digital data can be downloaded from the NERSL CD-ROM's. The COCORP atlas, for example, contains only small scale paper copies of processed data, including information on buying magnetic tapes containing the original field data. The NERSL CD-ROM provides processed data already in an industry standard format on compact high-capacity media at a greatly reduced cost.

After retrieving the digital information from the NERSL CD-ROM, the user can immediately process or redisplay the data using systems offering more advanced capabilities. Being able to use inexpensive hardware and public domain software to view and access large amounts of seismic-reflection data should provide users throughout government, academia, industry, and the scientific community in general with information needed to carry on a variety of important research projects.

Future enhancements to the NERSL CD-ROM products may include the addition of public domain well information located on or near the seismic lines residing on the disk. Appended software will allow the user to convert the well data into a synthetic seismogram which can be correlated with the actual seismic data. The well data would reside on the CD-ROM in an industry standard format so that it could be accessed and used by most commercial well log processing software packages. This feature would provide the scientist with the data and tools to correlate actual geologic information to seismic-reflection events.

NERSL developers are exploring the feasibility of using CD-ROM media for the storage and distribution of the original unprocessed field data. This may provide a solution to potential NERSL data storage problems and simultaneously provide the researcher raw data in a compact format which can be processed using the newest techniques. Occasional reprocessing of older data using state-of-the-art technology often supplies innovative solutions to geologic problems.

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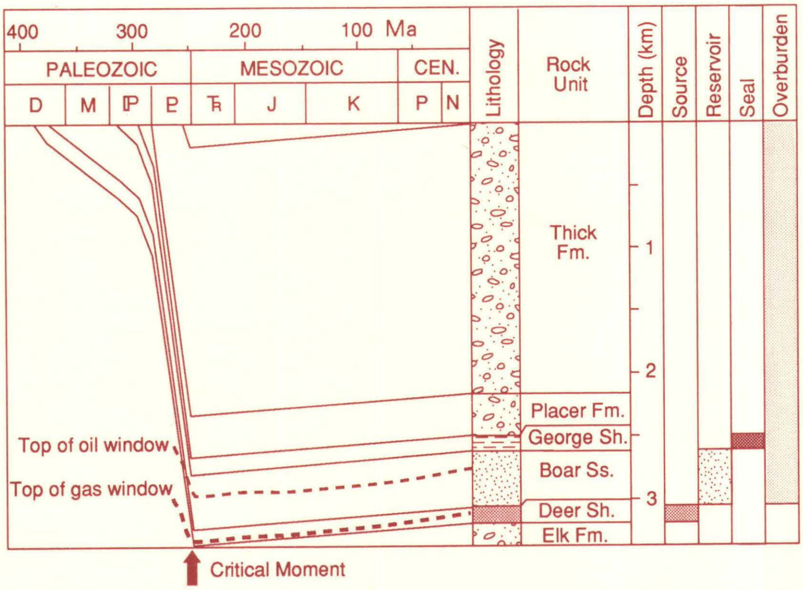


Figure 1. Burial history chart shows critical moment for Deer–Boar(.) petroleum system. Rock unit names are fictitious. Lithologies shown: conglomerate—Thick, Placer, and Elk Formations (Fm.); shale—George Shale (Sh.); sandstone—Boar Sandstone (Ss.).

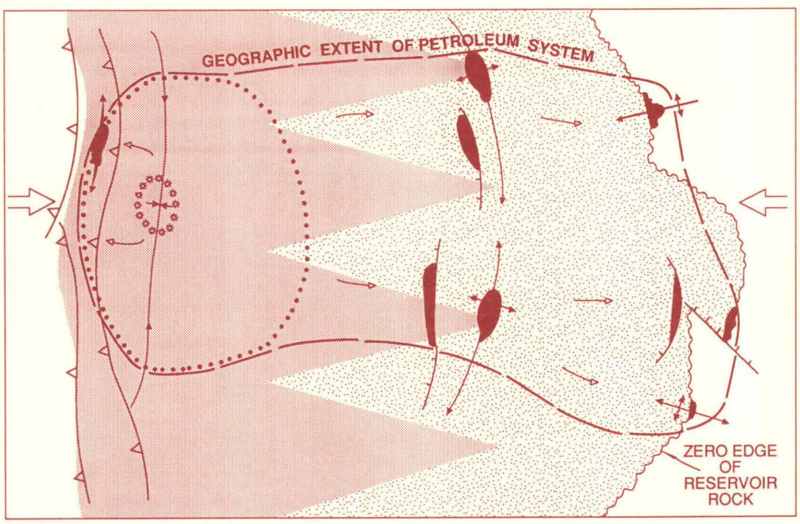
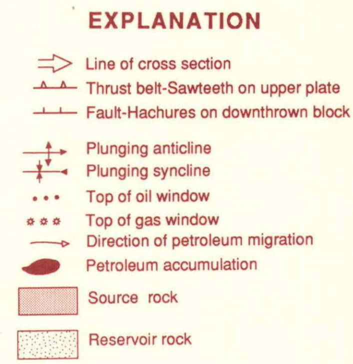


Figure 2. Geographic extent of Deer–Boar(.) petroleum system at critical moment.



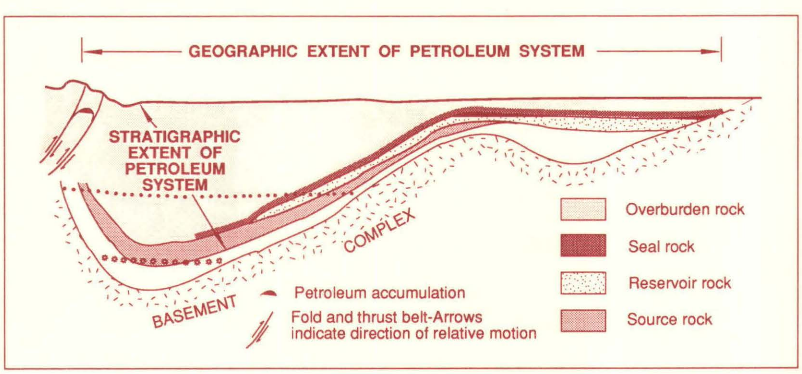


Figure 3. Geologic cross section showing stratigraphic extent of Deer–Boar(.) petroleum system at critical moment.

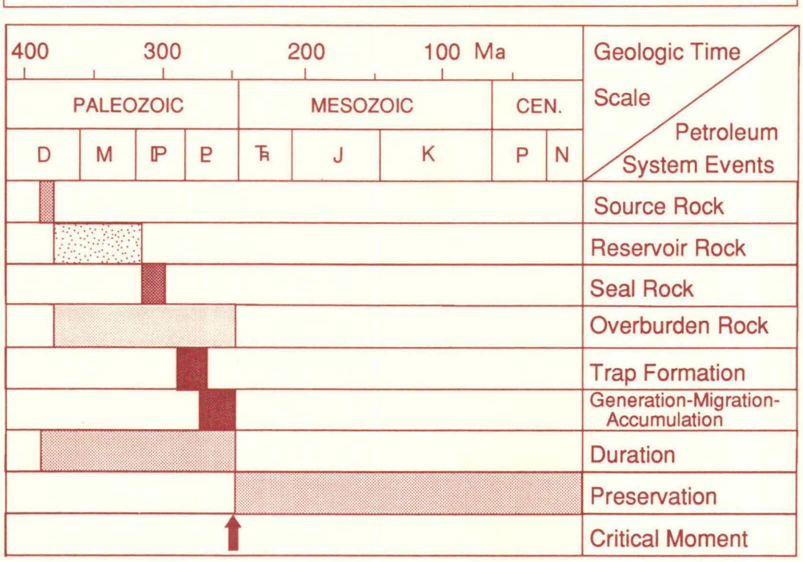


Figure 4. Events chart for Deer–Boar(.) petroleum system.